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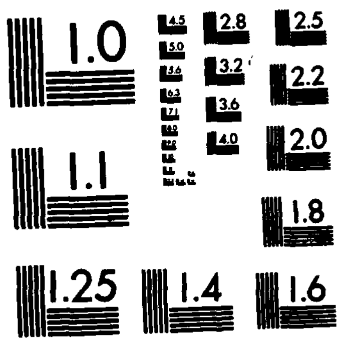
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A TRANSPORTATION MODEL FOR A
SPACE COLONIZATION AND MANUFACTURING SYSTEM:
A Q-GERT SIMULATION

THESIS

AFIT/GSO/OS/82D-6 Lynn A. Wagner, Jr.
Capt USAF

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY (ATC)
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GSO/OS/82D-6

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THESIS

Presented to the Faculty of the School of Engineering

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Master of Science

by

Lynn A. Wagner, Jr.

Capt USAF

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Preface

The purpose of this study was to develop a methodology for approaching the analysis of large transportation systems. While the study analyzed a transportation system for a space colonization and manufacturing system, the methodology is applicable to any transportation system.

This study started out as a class project for the Space Simulation course taught at the Air Force Institute of Technology by Lieutenant Colonel Thomas D. Clark. Captain John D. Rask, my co-worker on that project, and I developed a simple model for the transportation system during this course. Lieutenant Colonel Clark liked our approach and wished to see the methodology further developed. Captain Rask was unable to continue working on the project so I continued it on my own.

I would like to thank my thesis advisor, Lieutenant Colonel Clark for his invaluable assistance. I would also like to show my gratitude to my classmates, the first class of the graduate program in Space Operations, for being able to put up with me for the eighteen months of this program. Of my classmates, I would especially like to thank Captains Micheal L. Hunter and John D. Rask for reading parts of my thesis and giving some very good advice.

I wish to acknowledge my gratitude and love to my wife, Bienvenida, and to my three sons, Sean, Ian, and Aaron, for their love and support throughout this project. And finally, I would like to dedicate this work in memory of my father, Lynn A. Wagner, Sr., whose untimely death

several months prior to my entering AFIT has placed a great burden on both me and my family, and to my mother, Adeline Wagner, who has always given me all the support a son could ask for.

Lynn A. Wagner, Jr.

Contents

Contents

List of Figures

List of Tables

List of Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
ESS	Earth Space Station
GEO	Geostationary Earth Orbit
HLV	Heavy Launch Vehicle
IOS	Inter-Orbit Shuttle
IPSV	Interplanetary Space Vehicle
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LLV	Lunar Launch Vehicle
LMF	Lunar Mining Facility
LLS	Lunar Space Station
L1	Unstable Lagrangian Point One
L2	Unstable Lagrangian Point Two
L3	Unstable Lagrangian Point Three
L4	Stable Lagrangian Point Four
L5	Stable Lagrangian Point Five
NASA	National Astronautics and Space Administration
NSF	National Science Foundation
RPL	Rotary Pellet Launcher
SCMS	Space Colonization and Manufacturing System
SCS	Satellite Construction Shack
SSME	Space Shuttle Main Engine
SSPS	Satellite Solar Power System
STS	Space Transportation System

Abstract

A computer simulation model of a transportation system for a hypothetical Space Colonization and Manufacturing System (SCMS) was developed to show how the transportation system will possibly function. The model written in Q-GERT, a simulation language which allows a graphical presentation of the system, could be modified to experiment with different transportation strategies. While the SCMS is based mostly on current information, it is very likely that an entirely different system will eventually be developed. With this being the case, the main objective was not to just build a model for a particular system but to illustrate a methodology which could be used with another system.

The SCMS consist of six facilities in different orbits: three situated at Lagrangian points of the Earth-Moon system and the other three in low Earth orbit, geostationary Earth orbit, and low lunar orbit. The main activities of the SCMS are to build space colonies, to build Satellite Solar Power Stations, and to process lunar and asteroidal ore. The major component of the transportation system is the Inter-Orbital Shuttle which moves most goods between the points in the SCMS and is unloaded, serviced, and loaded at each of the facilities.

I. Introduction

On October 4, 1957 the Soviet Union surprised the world with the launch of Sputnik 1, the first artificial space satellite (Ref 1: 180). To many people this was the start of the "Space Age." While this may be true, the idea of space flight has been in the mind of man for centuries. Since the mid-1800's, authors have been writing about space flight and providing to their audiences glimpses of what could be. Jules Verne, considered by many people as the father of science fiction, fortold many of our modern achievements such as the landing men on the Moon (Ref 2). Could he also have given us another hint of the future: man living and working in space, that is, a space colony (Ref 3)?

In his article "Space Colonization Now?", Robert Salkeld gives a detailed and fascinating history of space colonization as protrayed in science fiction and scientific publications. Although space colonization for many years has been considered in the science fiction realm, it is slowly moving into the realm of science fact. Many prominent scientists in the twentieth century have voiced their views about space colonization from the Russian scientist Konstantin E. Tsiolkowsky in several works published in the late nineteenth and early twentieth centuries through Robert Goddard in private papers written around 1918 to Wernher von Braun in articles written in the 1950's for the magazine Coliers and in several books based on those articles. The present focal point for space colonization is a Princeton University physicist named Gerard K. O'Neill. Dr. O'Neill's first exposure to space colonization was an introductory Freshman Physics course that

Dr. O'Neill was teaching. As a class project he asked his students to look into the idea of space colonization. From the results that Dr. O'Neill and his students were getting, Dr. O'Neill thought that the idea appeared very feasible and further research was needed (Ref 4).

Since 1969 when Dr. O'Neill started researching the idea of space colonization and manufacturing (Ref 5), a large following of eminent scientists have examined the ideas and found them practical and achievable. In the years following Dr. O'Neill's initial research, Princeton University, the American Institute of Aeronautics and Astronautics (AIAA), the National Science Foundation (NSF), and the National Astronautics and Space Administration (NASA) have jointly sponsored five conferences on Space Manufacturing Facilities (Refs 6-10) to bring together scientists from many diversified areas to discuss the possibilities of space colonization and manufacturing. Also in the same vein, the NASA-Ames Research Center has sponsored several summer studies to further expand upon ideas from the conferences and other research (Refs 11-13). The results of these conferences and summer studies have indicated that the idea of space colonization and manufacturing is practical and achievable with present technology as long as there is a commitment from somewhere to provide the necessary capital to do the project.

During the years of research into the area of space colonization and manufacturing, researchers have analyzed several different designs for proposed space colonies/space manufacturing facilities as well as where to locate the facilities in the Earth-Moon system. Some of the major designs studied were:

1) a rotating cylinder (Ref 5),

2) a rotating torus (Ref 11), and

3) a rotating sphere (Ref 14).

All the above designs used extraterrestial material either from the Moon or an asteroid as the major portion of the total material needed to build the space colony.

For locating the space colony/space manufacturing facility, the initial idea was to place the colony at a stable point in the Earth-Moon system called L5 (see Chapter II for a description of L5) (Ref 5). In 1976 the suggestion was to place the facility at the 2:1 resonance orbit between the Earth and the Moon (see Ref 12 for more details). In 1977 Dr. O'Neill, in his book The High Frontier (Ref 14), suggested using a near-circular orbit with a period of a few weeks. Because of rapidly changing opinion of what type of orbit to place the space colony into, Dr. O'Neill suggests that L5 (at least in his book) should be thought of as "shorthand" for "whatever orbit the production engineers and celestial-mechanics experts finally settle on" (Ref 14: Preface).

To be able to make the idea of space colonization and manufacturing more attractive to the private sector, a product that could be sold at a profit to the Earth was needed. The researchers examined many alternatives from semi-conductor production to pharmaceutical products to supplying the Earth with high grade steel. Finally the researchers selected building Satellite Solar Power Stations (SSPS) to supply electricity to the Earth as the main product for space manufacturing (Refs 5-13). The idea for the SSPS was developed by Peter Glaser (Refs 15-16) in 1968 using the Space Transportation System (STS) to haul all needed materials from the Earth and utilizing on-orbit construction techniques to build the SSPSs. By using space colonies and extraterrestial material, the SSPS would become more cost effective.

For a space colonization and manufacturing system of this magnitude to work, there must be a means of transporting the terrestial or extraterrestial ore from its initial location to the point in the system where the ore will be processed to obtain _pure_ metals and non-metals. These processed or raw materials must then be transported to the site where they will be transformed into more space colonies or SPSS parts, which must then be transported to the location where the SPSSs will be constructed. Not only must there be a means of transporting the ore, raw materials, or SPSS parts between different sites in the system, there also must be a means of transporting people and different kinds of finished products between the same sites. Depending on the number of sites in the space colonization and manufacturing system, this could create an extremely large transportation system. A means of determining the _optimal_ transportation system will eventually be needed.

Problem

The problem investigated in this study was to develop a model of a transportation system for a hypothetical space colonization and manufacturing system that could be used to test hypotheses about the transportation system or the particular space colonization and manufacturing system used in this study. The goal is to see how particular assumptions about transportation affect the over-all colonization system.

Research Questions

Since the scientific area of space colonization and manufacturing is still in its infancy, it will be difficult to answer very specific questions on the feasibility of the project because of the lack of specific data. But by using existing general information, the following questions will be addressed:

1) Over a long period of time, how many inter-orbit shuttles (see Chapter 2 for an explanation of inter-orbit shuttles) will be needed in the system? To answer this question the following were assumed:

   a) an inter-orbit shuttle has approximately a ten year life expectancy,

   b) an inter-orbit shuttle can become severly damaged and therefor unusable, and

   c) the optimum number of inter-orbit shuttles will be taken as the number of shuttles that will allow a cargo of processed ore to always have immediate transportation from the ore processing facility to the production facility for SSPSs.

2) For the model proposed for the system (see Chapters 2 and 3), what are the parts of the model that most affect the final outcome of the model?

3) Is it cost effective to separate the tasks of processing lunar and asteroidal ore from the production of an SSPS? While it would probably be more economical to do the processing of the lunar and asteroidal ore and the production of SSPSs at the same location, it is not inconceivable that these tasks could

be seperated as are many processing and manufacturing plants on the Earth.

Objectives

The primary objective of this research was to provide an experimental model of a transportation system for a particular space colonization and manufacturing system. Intermediate objectives of this study were to:

1) Develop a computer simulation model/program that:
    a) will attempt to answer the stated research questions;
    b) will be easily modified when more detailed information, such as system parameters and costs, about space colonization and manufacturing become available; and
    c) will illustrate how much lunar and asteroidal ore must be processed to allow the system to be self-sufficient. Self-sufficiency means producing all the material to build the SSPSs and the space colonies and provide the fuel for the inter-orbit shuttles.
2) Develop a methodology or approach to the problem of space colonization and manufacturing which can be utilized in other situations.
3) Verify and validate the model/computer program.

Scope

The analysis and system design comprising this study assumes that all the chemical elements needed for building SSPSs and space colonies are contained in either the lunar or asteroidal ore and all components for the SSPSs and space colonies can be manufactured in space, that is, no components have to be built on the Earth. Since the exact chemical composition of a space colony or an SSPS has not been determined, but estimates of gross masses have been established, the study will keep track of the mass flow through the system and use mass relationships to determine the state of completion of a space colony or an SSPS. When detailed information about the chemical composition has been determined, the information can be incorporated into the model.

Several parameters of the model have been estimated because there is no detailed information about them. A sensitivity analysis will be done on these parameters to see how they effect the overall model.

Background

Producing a transportation model for a space colonization and manufacturing system has not received much attention to date. While many researchers looked at the mechanics of moving lunar material, asteroids, and space vehicles between certain points in the system and the type of space vehicle to use (Refs 5-14, 23), a complete space transportation model has not been presented.

The 1975 NASA-Ames Summer Study discussed a transportation model for their space colony. The study presented the model pictorally and described the space vehicles that were needed. The study gave estimates of how many vehicles were needed but never said how these estimates were derived. The following are the estimates (Ref 11: 60-61, 80-82, 139-149):

1) Space Shuttles = 3,
2) Heavy Lift Launch Vehicles = 6,
3) Interorbit Transport Vehicles = 9,
4) Lunar Landing Vehicles = 4, and
5) Inter-Libration Transfer Vehicles (Lunar Ore Carriers) = 2

David L. Akin in his paper "Optimization of Space Manufacturing Systems" for the 4th Princeton/AIAA Conference on Space Manufacturing (Ref 9: 257-266) discussed techniques for arriving at the optimal payload mass versus launch cost per kilogram of payload for a vehicle launched from the surface of the Earth, techniques for arriving at the optimal exhaust velocity (and therefore the optimal type of space vehicle) versus payload cost per kilogram of payload for an interorbital space vehicle, parametric analysis of the SSPS production system, and a linear programming technique to determine the optimal blend of SSPS production stratagies. While he presented several techniques he did not tie them together to get an overall optimal stratagy.

As was the case with the Akin study, most studies tried to optimize parts of the system but did not try to either determine a complete optimal system or show how their optimal part affected the overall system. This could cause problems with the entire system. For example, the optimum size of a space vehicle's payload is determined based on a set of criteria such as cost, amount of polution, etc. If the "optimal" space vehicle is used, then it is possible that, for the overall system, it would require more trips to do the mission than using a "non-optimal" space vehicle and therefore cost more money and produce more polution. In this situation, the overall system would be non-optimal.

A new approach to the problem is needed which can be used to produce an optimal system and/or show how changes to the system affect the entire system. The methodology which is presented in this study will attempt to get an optimal system solution based on a particular set of criteria (see Chapter III, Model Formulation, for a discussion of the criteria). The method will also allow the user to change parameters in the model and see if the change helps or hinders the system. The selection of the methodology is discussed in the next section and the implementation of it is presented in Chapter III.

Methodology

There are many ways to develop a space colonization and manufacturing systems depending on what tasks must be accomplished in the system and on where the task will be done. The Space Colonization and Manufacturing System (SCMS) used in this study (see Chapter II) is only one example of a possible system. To accomplish some of the tasks for the SCMS, a transportation system is needed. Based on the mission of the SCMS and the preference of system's designer, several different types of transportation systems could be used. Since it would be impossible to describe all the possible variations of a transportation system, only a few methods will be given.

One method, similar to the method used in the 1975 NASA-Ames Summer Study, is to have a transportation system which uses a different type of space vehicle to do each type of mission, that is, transporting a particular type of cargo between points in the system. If this is done and if the analyst knows the number of cargos which must be transported, the exact travel times between points in the system, and the exact lingering times of a space vehicle at any point, it is possible to analitically calculate the number of space vehicles that will be needed. The problems with this approach is that the times used in the model must be deterministic and that the model does not take into account damage and age of the space vehicles.

Another method is to use only one type of space vehicle which will allow mass production of the vehicles and thus reduce the per copy cost. This will also alleviate the need for several production lines to be in operation at one time. The main disadvantage with this method is that the space vehicles must be designed to withstand any environment.

The last method, the one used in this study, is a combination of the two previous methods which tries to keep the advantages of the other methods while eliminating some of the disadvantages. The method is to have one type of space vehicle, Inter-Orbit Shuttle (IOS), doing all the transporting of cargo between points in the system with three exceptions. (There is a precedence for this in the United States' present policy of having the STS as the backbone of the space program but using expendable space launch vehicles as backups.) Because it probably would be infeasible, economically, to build a space vehicle which could transport large cargos and then be able to handle the stress of landing and taking-off from the Earth or the Moon, special launch vehicles, the Heavy Launch Vehicle (HLV) and the Lunar Launch Vehicle (LLV), were developed for the Earth and the Moon. The third exception is the Interplanetary Space Vehicle (IPSV) which is used to recover asteroids. The IPSV would be used to transport cargos in the million metric ton range over a duration of years while the IOS would be used with cargos in the thousand metric ton range over a duration of weeks. These three new vehicles will be used mainly to input cargos into the SCMS and will not therefore be directly modeled in the computer program. If the need arrises for these vehicles to be modeled, it would be very easy to incorporate them into the model.

At the different points of the system, cargo will arrive from either the Earth, the Moon, or the asteroid belt; lunar and asteroidal ore will be processed; and IOSs will be unloaded, serviced, and loaded. Because a real space colonization and manufacturing system is not in existence to determine exact arrival rates, travel times, and service times, the above processes will be best modeled as stochastic rather than deterministic processes with probabilistic arrival rates, travel times, and service times. Budnick, et al, have stated that "a queue forms whenever existing demand exceeds the existing capacity of the service facility, that is, whenever arriving customers cannot receive immediate service due to busy servers. This state of affairs is almost guaranteed to occur at some time in any system which has probabilistic arrival and servicing patterns (Ref 17: 429)." Because of this fact, a queueing theory approach was utilized in the model.

<u>Queueing Theory</u>. "Queueing theory involves the mathematical study

of 'queues,' or waiting lines (Ref 18: 400)."

> The basic process assumed by most queueing models is the following. "Customers" requiring service are generated over time by an "input source." These customers enter the queueing system and join the queue. At certain times a member of the queue is selected for service by some rule known as the queue discipline (or service discipline). The required service is then performed for the customer by the service mechanism, after which the customer leaves the queueing system (Ref 18: 401).

The queueing process is depicted in Figure 1.1. If more detailed information on queueing theory is needed, the reader should review any good operations research text such as Introduction to Operations Research by Hillier and Leiberman (Ref 18).

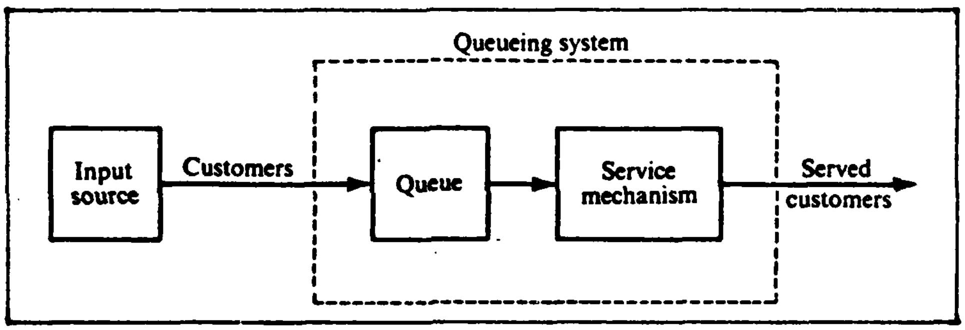


Figure 1.1 The Queueing Process (Ref 18: 402)

For large, complicated systems such as the one described in this study, there are two basic ways to solve the problem: analytically and by simulation. An analytical approach was considered but found difficult to do because at the present time, there are only analytical techniques for simple queueing models. Because of the complexity of the SCMS, it would be extremely difficult, if not impossible, to cast the model at the level where an analytical solution is feasible.

To be able to model the use of one type of space vehicle for transporting cargo between points in the SCMS and the use of queueing theory at the different points in the system, simulation was selected as the tool to implement the transportation model. Once the decision was made to use simulation, a computer language was needed. A general purpose language, like FORTRAN or Pascal, could be used but the complexity of the model would probably require that the program be several thousand lines long. Therefore, a special purpose language was needed. The simulation language choosen was Q-GERT.

Q-GERT. In his book, A. Alan B. Pritsker, the developer of Q-GERT, gives a detailed history of its development (Ref 19: 11-17). Q-GERT is

> a new technique ... which can be used for modeling and analyzing a class of procedural systems. Q-GERT involves the graphical modeling of systems in a network form. Q-GERT networks provide a vehicle through which information about models of procedural systems can be communicated. Q-GERT networks can be analyzed automatically to provide statistical information about the system under study (Ref 19: 2).

Dr. Pritsker also gives a comprehensive description of how Q-GERT networks operate (Ref 19: 3-4):

> Q-GERT employs an activity-on-branch network philosophy in which a branch represents an activity that involves a processing time or a delay. Nodes are used to seperate branches and are used to model milestones, decision points, and queues. A Q-GERT network consists of nodes and branches. Flowing through the network are items referred to as transactions. Transactions are directed through the network according to the branching characteristics of the nodes. Transactions can represent physical objects, information, or a combination of the two. Different types of nodes are included in Q-GERT to allow for the modeling of complex queueing situations and project management systems. Activities can be used to represent servers of a queueing system and Q-GERT networks can be developed to model sequential and parallel service systems. The nodes and branches of a Q-GERT model describe the structural aspects of the system. A process approach ... is taken in which the flow of a transaction is modeled.

Transactions originate at source nodes and travel along the branches of the network. Each branch has a start node and an end node as shown below [see Figure 1.2]. Transactions moving across a branch are delayed in reaching the end node associated with the branch by the time to perform the activity that the branch represents. When reaching the end node, the disposition of the transaction is determined by the node type, the status of the system, and the attributes associated with the transaction. The transaction continues through the network until no further routing can be performed. Typically, this occurs at sink nodes of the network but may occur at other nodes to allow for the destruction of information flow.

Transactions have attribute values that allow different types of objects (or the same type of object with different attribute values) to flow through the network. Procedures are available to assign and change attribute values of transactions at various nodes of the network.

As transactions flow through the network model, statistics are collected on travel times, the status of servers and queues, and the times at which nodes are released. Thus, a statistical data collection scheme is embedded directly in a Q-GERT network model. The Q-GERT Analysis Program employs a simulation procedure to analyze the network. The simulation procedure involves the generation of transactions, the processing of the transactions through the network, and the collection of statistics required to perform automatically a summary report as dictated by the Q-GERT network model.

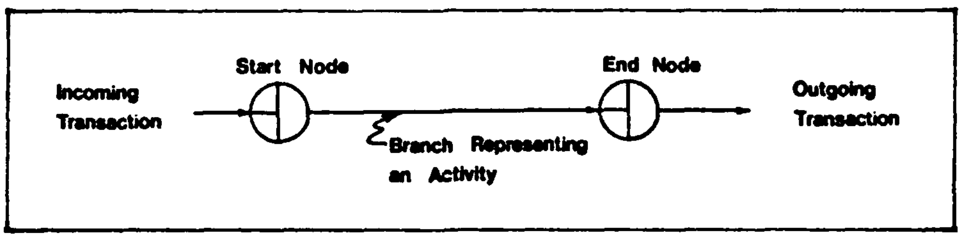


Figure 1.2 A Q-GERT Illustration (Ref 19: 4)

Conclusion. The approach used in this study is to model the transportation system for the Space Colonization and Manufacturing System (SCMS) as a large queueing system. The queueing system will be solved using simulation, in particular, using a Q-GERT network description of the SCMS. The SCMS, the transportation system, and the Q-GERT network will be described in the remaining chapters.

Overview of Thesis

Discussed in Chapter II is the conceptual model for a Space Colonization and Manufacturing System (SCMS). The SCMS is broken down into subsystems and the parts of the subsystems are decribed. The orbits and space vehicles used in the SCMS are also described.

Described in Chapter III is the computer model of the transportation system for the SCMS. The model is discussed in terms of the Q-GERT structure which implements the model. The verification and validation of the computer model are also decribed.

An experimental design that can be used to test transportation alternatives is described in Chapter IV. The experimental design can also be used to test assumptions about the SCMS.

Presented in Chapter V is a summary of the report, conclusions, and recommendations for continued study.

Summary

Discussed in this chapter is the history of research into space colonization and manufacturing systems. Presented in the chapter is the problem along with research questions, the objectives of the study, and the scope of the research. A brief background on previous research into space transportation systems was presented along with the methodology used in approaching the development of a space transportation model. In the next chapter the Space Colonization and Manufacturing System will be described.

II. A Space Colonization and Manufacturing System (SCMS)

Introduction

The Space Colonization and Manufacturing System (SCMS), that will be used in this study, will be described in this chapter . The SCMS, in most details, will parallel the system developed by the 1975 NASA-Ames Summer Study (Ref 11), but will incorporate several items not addressed in that summer study. The SCMS will consist of six major parts or subsystems which take their names from the physical location that they occupy in the Earth-Moon system:

1) Low Earth Orbit (LEO),
2) Geostationary Earth Orbit (GEO),
3) Low Lunar Orbit (LLO),
4) Unstable Lagrangian Point Two (L2),
5) Stable Lagrangian Point Four (L4), and
6) Stable Lagrangian Point Five (L5).

The major constituents or elements of each subsystem will be described in general terms to allow the reader to get an idea of what will be needed in a space colonization and manufacturing system. Specific examples for some elements will be given, but it should be understood that these are only examples and any similar element, which accomplishes the desired mission, could be used without affecting the transportation model described in Chapter III. An exception to this is when the element selected changes either the mass flow in the system or a process time for an activity. If this happens, then the transportation model will have to be changed accordingly.

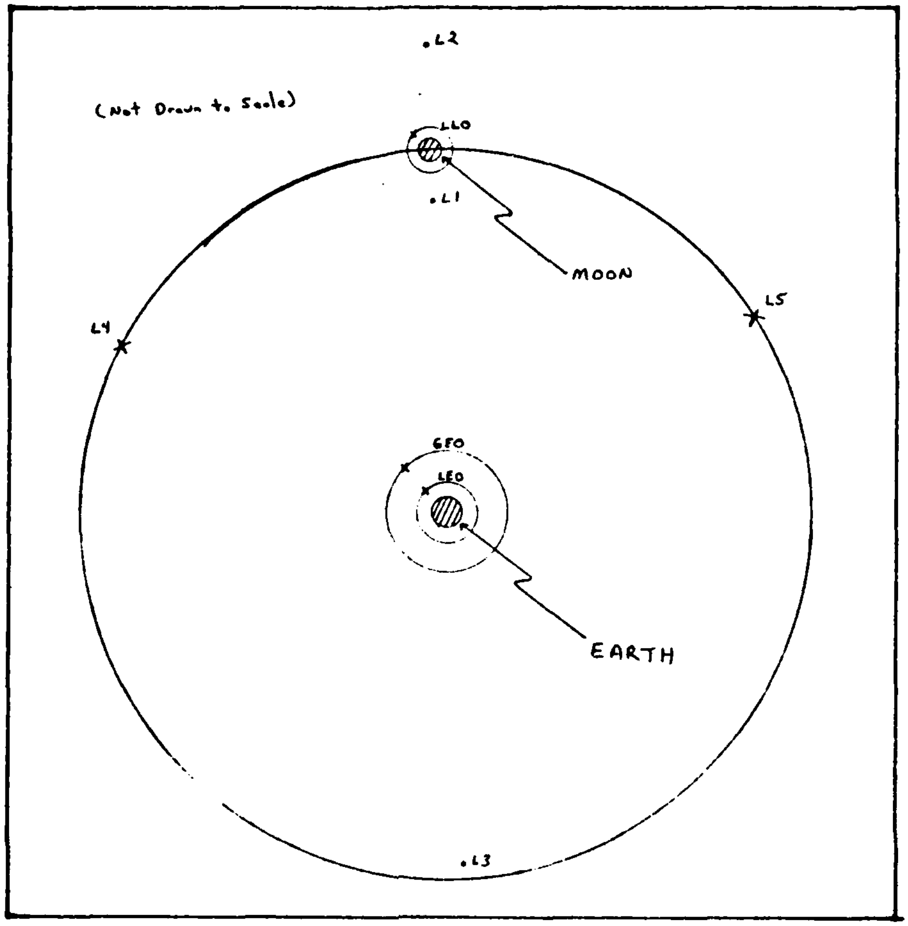


Figure 2.1 The Earth-Moon System

As mentioned previously, the names of the subsystems are related to their position in the Earth-Moon system (see Figure 2.1) but, as will be shown in Chapter III, the subsystems are distinguished from each other not by position but by the flight times between them. It will, therefore, be possible to "move" the site of a subsystem to match what the production engineers and celestial-mechanics experts finally settle on. Before describing the subsystems of the SCMS, the Earth-Moon system and the space vehicles used in the SCMS will be described.

TABLE I

Data On The Earth-Moon System

ELEMENT	SYMBOL	VALUE
Mass of the Earth	M_1	5.972×10^{27} gm.
Radius of the Earth	r_1	6378.160 km.
Mass of the Moon	M_2	7.344×10^{25} gm.
Radius of the Moon	r_2	1738 km.
Semi-Major Axis of the Lunar Orbit	a_M	384,400 km.
Eccentricity of the Lunar Orbit	e_M	0.05490
Inclination of the Lunar Orbit	i_M	5.13 deg.
Period of the Moon	P_M	27.32166 days
Distance from the Earth to L1	$a_M(1 - R_1)$	326,400 km.
Distance from the Earth to L2	$a_M(1 + R_2)$	449,000 km.
Distance from the Earth to L3	$a_M(1 - R_3)$	381,700 km.

TABLE I (Cont.)

Data on the Earth-Moon System

ELEMENT	SYMBOL	VALUE
Distance from the Moon to L1	$a_M(R_1)$	58,040 km.
Distance from the Moon to L2	$a_M(R_2)$	64,620 km.
Distance from the Moon to L3	$a_M(2 - R_3)$	766,100 km.
Distance from L4 to L5	$2a_M \sin(60 \text{ deg.})$	665,800 km.
Semi-Major Axis of LEO	a_{LEO}	6804 km.
Inclination of LEO	i_{LEO}	28.5 deg.
Semi-Major Axis of GEO	a_{GEO}	42,120 km.
Inclination of GEO	i_{GEO}	0.0 deg.
Semi-Major Axis of LLO	a_{LLO}	1988 km.
Inclination of LLO	i_{LLO}	0.0 deg.

SOURCE: Kenneth R. Lang, Astrophysical Formulae, pp. 524-526, 540-544. (For non-calculated data on the Earth, Moon, and Lunar Orbit)

The Earth-Moon System

The "orbits" used in this study will be described in this section. The relationship between the different subsystems of the SCMS is shown in Figure 2.1 while important information about the Earth-Moon system and the SCMS "orbits" is given in Table I. If more detailed information on orbital theory is needed, the reader should review a good book on celestial mechanics such as Methods of Celestial Mechanics by Dirk Brouwer and Gerald M. Clemence (Ref 20).

Earth Orbits. In the SCMS there will be two Earth orbits utilized. The first will be a low Earth orbit (LEO) which will be the orbit of a Earth Space Station (ESS). The orbit selected will be a near-circular orbit with an altitude/inclination of 426 km./28.5 deg. which is the same as the orbit used in a NASA space station proposal (Ref 21). The second orbit will be a geostationary Earth orbit (GEO) which will be the orbit where SSPSs will be placed. This is a near-circular orbit with an altitude/inclination of 35,740 km./0.0 deg. and has a period of 23 hours 56 minutes (the time for one revolution of the Earth) which causes the SSPS to appear to remain "fixed" over one location on the Earth's equator.

Lunar Orbit. The SCMS will utilize only one orbit around the Moon which will be used by a Lunar Space Station (LSS). The low lunar orbit (LLO) will be a near-circular orbit and will have an altitude/inclination of 426 km./0.0 deg. with respect to the Moon.

Lagrangian Points. One of the major areas of celestial mechanics is trying to find solutions to the n-body problem.

The problem of describing the motion of a number of mutually attracting bodies has been studied at length for many decades. Analytical results are quite limited, because the n-body problem has only 10 known integrals of motion: 3 velocity components, 3 position components, 3 angular momentum components, and kinetic energy. The relative motion of two bodies requires 6 of these, but the three-body problem requires 12 integrations for relative motion and 18 for the general solution. Therefore, only the two-body problem has an unrestricted solution. Special cases of the three-body problem have been treated in closed form, and these are known as the restricted three-body problems ... (Ref 22: 25).

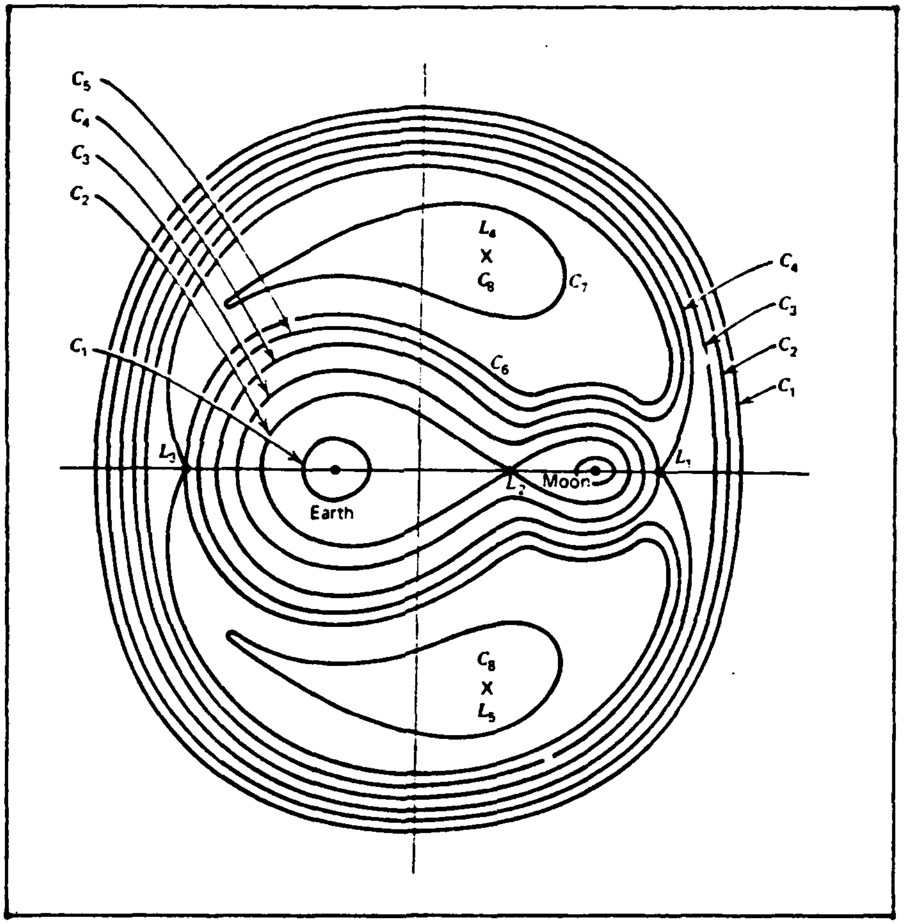


Figure 2.2 Contours Of Zero Relative Velocity (Ref 21: 294)

An example of a restricted three-body problem is a system with two large masses, like the Earth and the Moon, and a small body with a

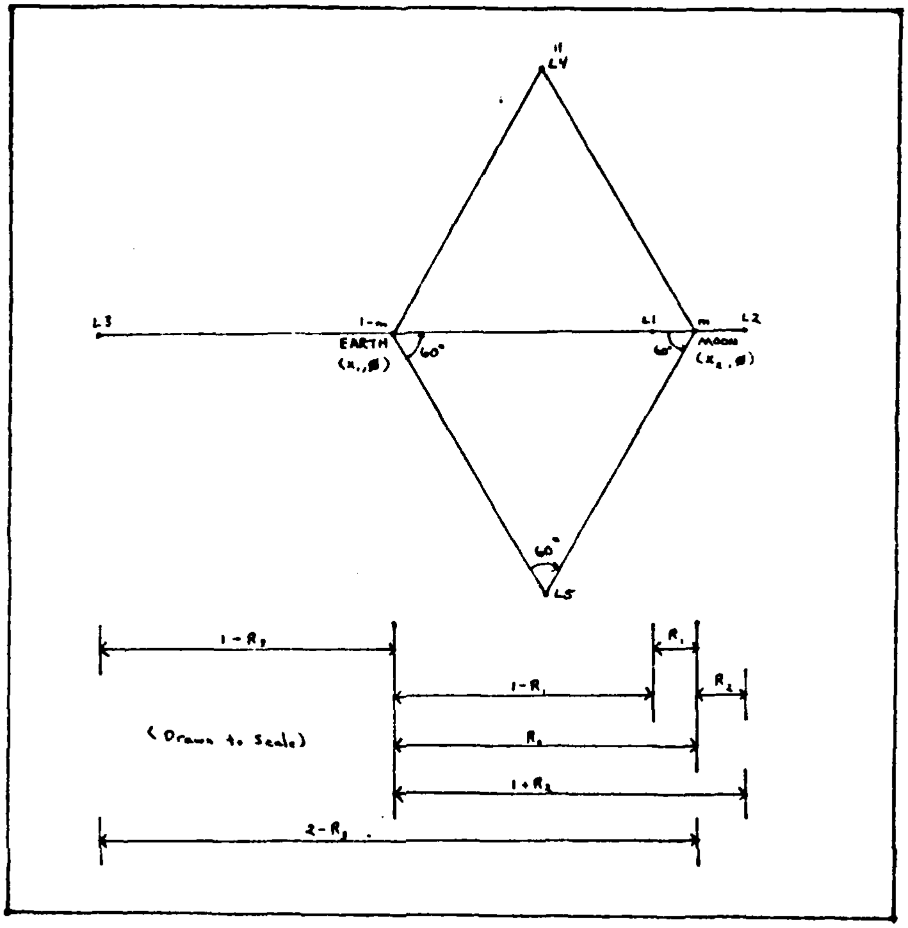


Figure 2.3 Lagrangian Points For The Earth-Moon System

negligible mass, such as a satellite or space colony. A plot of contours of zero relative velocities for the Earth-Moon-satellite system where C1 > C2 > C3 ... is given in Figure 2.2. These loci of zero relative velocitiy positions correspond to constant potential energies. By examining this figure it can be seen that there are potential energy <u>wells</u> in the neighborhood of both the Earth and the Moon, <u>peaks</u> at the equilateral triangular points L4 and L5, and <u>saddle points</u> at the straight line points L1, L2, and L3. The five Lagrangian or libration points (L1, L2, L3, L4, and L5) are the "solutions" or equilibrium points of the restricted three-body problem in celestial mechanics (Ref 22: 289-294). Brouwer and Clemence present the mathematics of the solution to the restricted three-body problem (Ref 20: 253-262) which was originally solved by the French astronomer and mathematician Count Joseph Louis Lagrange in the late 1700's.

The straight line solutions (L1, L2, and L3) are unstable equilibrium points. That is, if an object is placed at any of these points, the object will remain there as long as it is not disturbed; but if it is slightly disturbed, the object will leave the Lagrangian point. The equilateral triangle solutions (L4 and L5) are stable equilibrium points. An object will tend to remain around these points even if it is slightly disturbed. If the Sun's influence is included in the problem (a restricted four-body problem), then L4 and L5 are no longer stable points. Even though they are not stable points, there exist "orbits" around L4 and L5 which are stable (Ref 23). This study will treat L4 and L5 as points not orbits around points even though the model in Chapter III will not know the difference.

The SCMS will have subsystems at three Lagrangian points (L2, L4, and L5) with a lunar SSPS at L1. The relationship between the five Lagrangian points, the Earth, and the Moon is shown Figure 2.3 with information about this relationship in terms of distances between points given in Table I. Some of the equations used in deriving the relative distances between points in the system are listed in Table II. Because the numbering system for the Lagrangian points vary with authors, the system employed in this study matches the one used in the AIAA conference reports (Ref 6-10) (see Figures 2.1 and 2.3).

TABLE II

<u>Lagrangian Point Calculations</u>

$$m = M_2 / (M_1 + M_2) = 0.01215$$

$$1 - m = M_1 / (M_1 + M_2) = 0.98790$$

$$m / (1 - m) = M_2 / M_1 = 0.01230$$

$$A = \{m / [3(1 - m)]\}^{1/3} = 0.1600$$

$$(1 - m)X_1 + mX_2 = 0$$

$$R_0 = X_2 - X_1 = 1$$

$$R_1 = A(1 - (1/3)A - (1/9)A^2 - \dots) = 0.1510$$

$$R_2 = A(1 + (1/3)A - (1/9)A^2 + \dots) = 0.1681$$

$$R_3 = (7m/12)(1 + (23/84)(7m/12)^2) = 0.007088$$

Space Vehicles

The SCMS will use four different types of space vehicles. These vehicles will be used to transport cargo between points in the SCMS. Since each of the vehicles have their own mission, the space vehicles are not interchangable.

Inter-Orbit Shuttles (IOS). The Inter-Orbit Shuttle is used to transport cargo between the major subsystems (LEO, GEO, LLO, L2, L4, and L5) of the SCMS. The IOS can transport large quantities of cargo between these points but is not structurally strong enough to land on either the Earth or the Moon. The 1975 NASA-Ames Summer Study determined that a lunar landing vehicle with one space shuttle main engine (SSME) could land over 900 metric tons on the lunar surface (Ref 11: 60). A space vehicle equiped with two SSME's could easily transport a cargo of 1500 metric tons which is the assumed capacity of an IOS used in this study. An IOS could also use a mass driver (see the section on L2 for a description of a mass driver) or ion engines as its means of propulsion but the travel times between points in the system will probably be longer than an IOS equiped with a chemical engine like the SSME.

Heavy Launch Vehicle (HLV). The Heavy Launch Vehicle is a completely reusable launch vehicle which is employed to transport cargo between the Earth's surface and low Earth orbit. NASA is looking at a Space Shuttle based HLV which would have a capacity greater than 150 metric tons (Ref 7: 51-60). The HLV used in this study is assumed to have a capacity equal to the capacity of an IOS. If this is not true, it then can be assumed that multiple (or fractional) launches can equal one proposed HLV launch or that the IOS leaves LEO only partially loaded. The STS is not specifically incorporated into the SCMS but it can be assumed that multiple STS launches can equal one HLV launch.

Lunar Launch Vehicle (LLV). The Lunar Launch Vehicle, a completely reusable launch vehicle, is used to transport cargo between the Moon's surface and low lunar orbit. The LLV used in this study is assumed to have a capacity equal to the capacity of an IOS. If this is not true, it can be assumed that multiple (or fractional) launches can equal one proposed LLV launch or that the IOS leaves LLO only partially loaded.

Interplanetary Space Vehicle (IPSV). An Interplanetary Space Vehicle has the capability to leave the Earth-Moon system and rendezvous with an asteroid whose orbit crosses the Earth's orbit or an asteroid in the asteroid belt. After rendezvous with the asteroid, the IPSV, utilizing a mass driver propulsion system, will bring the asteroid back to L5. The 1977 NASA-Ames Summer Study discussed using a mass driver powered space vehicle to retreive Earth crossing asteroids and to bring them back to the Earth-Moon system (Ref 13: 159-204).

Low Earth Orbit (LEO)

The SCMS will require an Earth Space Station (ESS) to reside in low Earth orbit. The ESS will recieve HLV from the Earth and transfer the HLV's cargo to an IOS for transport to oth parts of the SCMS. By having an ESS, the HLV can be a smaller launch vehicle while still delivering the same amount of cargo into space; the HLV can be launched even when an IOS in not available; and an IOS can deliver a cargo to LEO even when a vehicle is not waiting to deliver the cargo to the Earth's surface. The ESS has the capability to load and unload both the HLV and the IOS but only the IOS capability has been incorporated directly into the transportation model. The ESS also has the capability to do minimum servicing, such as fueling (only L5 has the capability to do major repairs), on the IOS.

Geostationary Earth Orbit (GEO)

The Satellite Solar Power Station (SSPS), the major product of the SCMS, will be constructed in geostationary Earth orbit to supply the Earth with inexpensive electrical power from sunlight. The SSPSs are built in parts and then transported in IOSs to GEO to be constructed. To accomplish this mission, a Satellite Construction Shack (SCS) will be needed to house the crew who will put together the SSPSs. The SCS must also have the capability to unload, service (minimum), and load IOSs. If needed, the SCS could be moved to a new location after an SSPS is completed.

The SSPSs could be constructed where the parts are built (Ref 11) and slowly transported under their own power to GEO. This would require many months of transport time and an SSPS to have its own propulsion system that may never be used again. Because the number of different types of space vehicles that transport cargo in the SCMS was to be kept at a minimum, it was decided to do the construction at GEO.

Low Lunar Orbit (LLO)

The SCMS subsystem at LLO is conceptually identical to the subsystem at LEO except this subsystem is in lunar orbit. The SCMS will require an Lunar Space Station (LSS) to reside in low lunar orbit. The LSS will recieve LLV from the Moon and transfer the LLV's cargo to an IOS for transport to other parts of the SCMS. By having an LSS, the LLV can be a smaller launch vehicle while still delivering the same amount of cargo into space; the LLV can be launched even when an IOS in not available; and an IOS can deliver a cargo to LLO even when a vehicle is not waiting to deliver the cargo to the Moon's surface. The LSS has the capability to load and unload both the LLV and the IOS but only the IOS capability has been incorporated directly into the transportation model. The LSS also has the capability to do minimum servicing on the IOS.

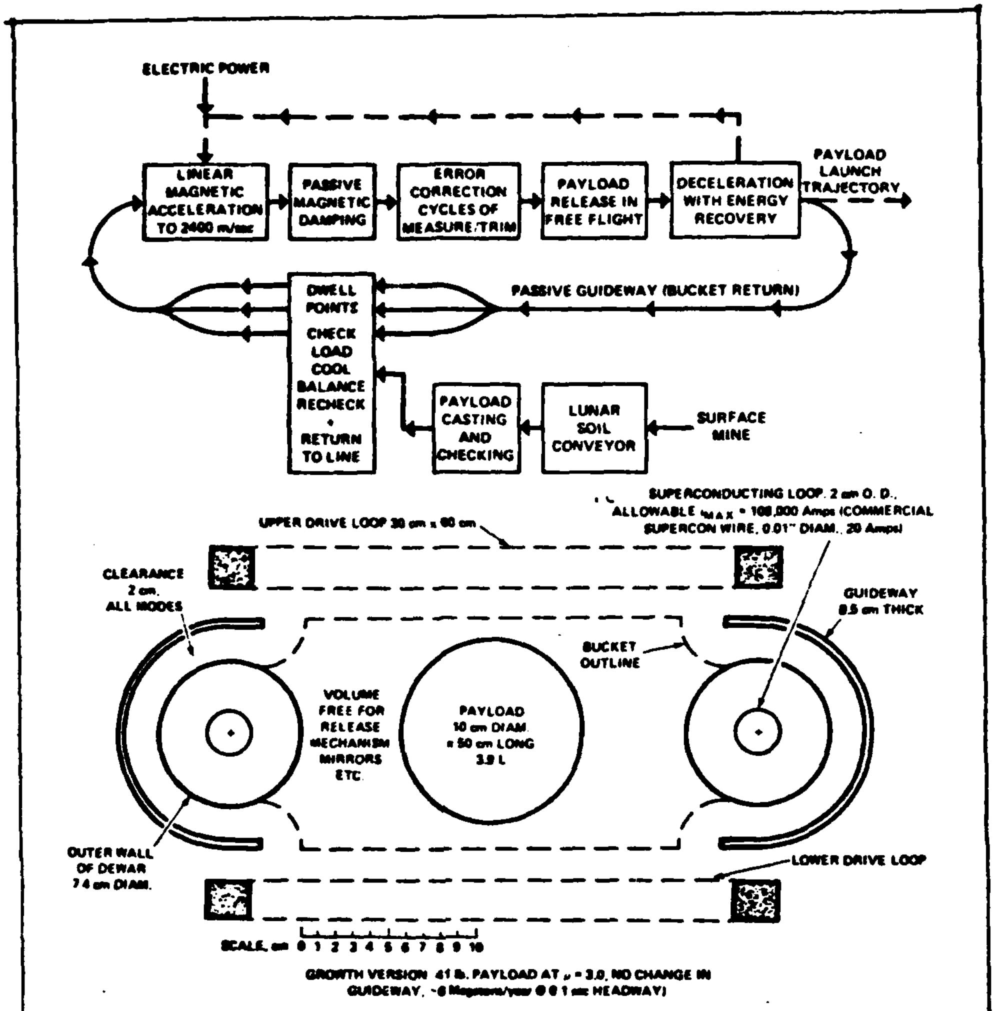
Unstable Lagrangian Point Two (L2)

The L2 subsystem of the SCMS not only contains the facilities in orbit at L2 but also facilities on the lunar surface. The facilities on the lunar surface will mine the lunar ore, prepare it for shipment to L2 via mass driver, and send the ore to L2 to be captured by a mass catcher. The SCMS will also require a small space station at L2 which will house the crew for the mass catcher and the IOS service facility. The space station will have the facilities to prepare the lunar ore for shipment to L5 and will also have the capability to unload, service (minimum), and load IOSs.

Lunar Mining Facility (LMF). The Lunar Mining Facility (LMF) mines lunar ore and packages the ore for shipment to L2. The LMF will be located in the Cayley area of the Moon (4 deg. N., 15 deg. E.) where Apollo 16 landed. This site was choosen because of "the richness of the lunar ore," "the suitably flat terrain" for the mass driver launcher, and "the near-side equatorial region gives a suitable trajectory" to L2 (Ref 11: 106). Even though the Cayley area was choosen, it is not the best site for the mass driver. The best site for the mass driver is at 33.1 deg. east logitude, near the craters Censorinus and Meskelyne (Ref 23: 89). The "best site" was not choosen because of the lack of knowledge of the composition of the lunar ore at that site.

The lunar ore will be used in building space colonies at L4 and L5 and building SSPSs. The lunar ores are not rich, but they are adequate. They contain plagioclase and anorthosite which are sources of aluminum, ilmenite which is a source of titanium and iron, and silica. Silica, which on the Earth is a useless waste product, is of value in space. The ores also contain oxygen chemically bound to the metals and the silicon (Ref 23: 79-80). The Cayley area has a aluminum content of between 4.5 and 14.4 percent (Ref 11: 106).

Mass Driver. "In brief, a mass driver is an electrically driven machine for the conversion of energy into kinetic form as high-velocity payloads, each of which is some tens of kilograms. A small vehicle (bucket) containing superconducting coils is supported and quided without physical contact by dynamic magnetic levitation. It is accelerated by magnetic fields as the armature of a linear synchronous motor, releases its payload, is decelerated magnetically with return of energy to the power supply, and then recirculates to pick up and



Centering forces within a mass-driver guideway, here shown in cross-section with a bucket, would reach 30-g for a displacement of 1 cm. A growth version carrying 41-lb batches of payload at 0.1-sec headway could fire off about 6 megatons per year with no change in the guideway.

Figure 2.4 Concept For A Mass Driver (Ref 12: 7)

accelerate another payload (Ref 12: 64)."

A mass driver (see Figures 2.4, 2.5, and 2.6), designed by the 1976 NASA-Ames Summer Study, could deliver 600,000 metric tons of lunar ore to L2 assuming that the LMF has either a nuclear power plant or a dedicated SSPS at L1, which is the Moon's version of a geostationary

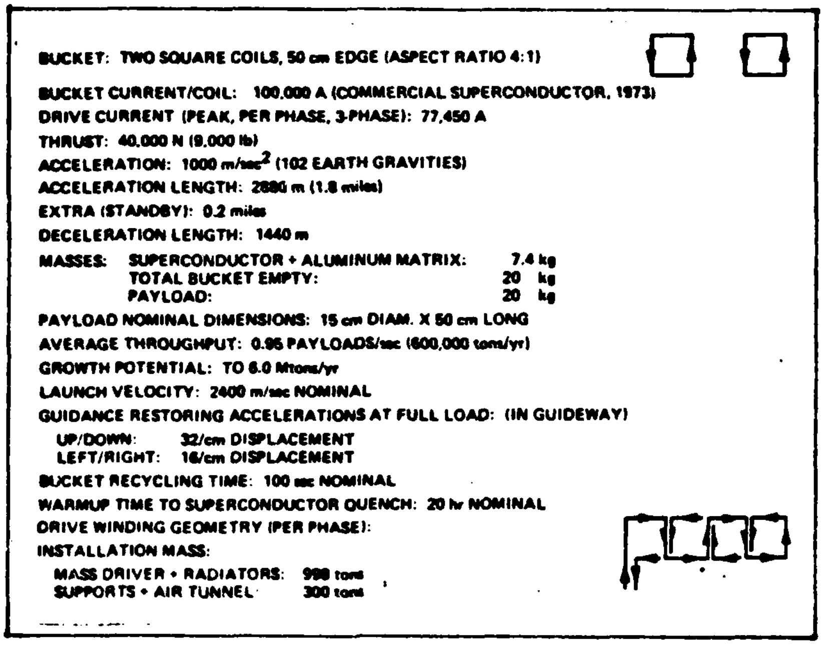


Figure 2.5 Design For A Mass Driver (Ref 12: 73)

orbit. The SSPS is needed to supply power to the LMF during the 14-day lunar night. The mass driver could accelerate 20 kg. packets at a rate of approximately one packet per second to the lunar escape velocity: 2400 m/sec (Ref 12: 73). The packets of lunar ore would be packaged in fiberglass sacks which are manufactured at the LMF out of lunar soil (Ref 12: 125-126).

Mass Catcher. Once the mass driver propels the lunar ore packets from the lunar surface, there must be a way to capture the packets for shipment to L5. A mass catcher is placed at L2, considered the best receiving point for collecting lunar material (Ref 12: 22), to do this task. The mass catcher is a device which either passively or actively "catches" the lunar ore packets.

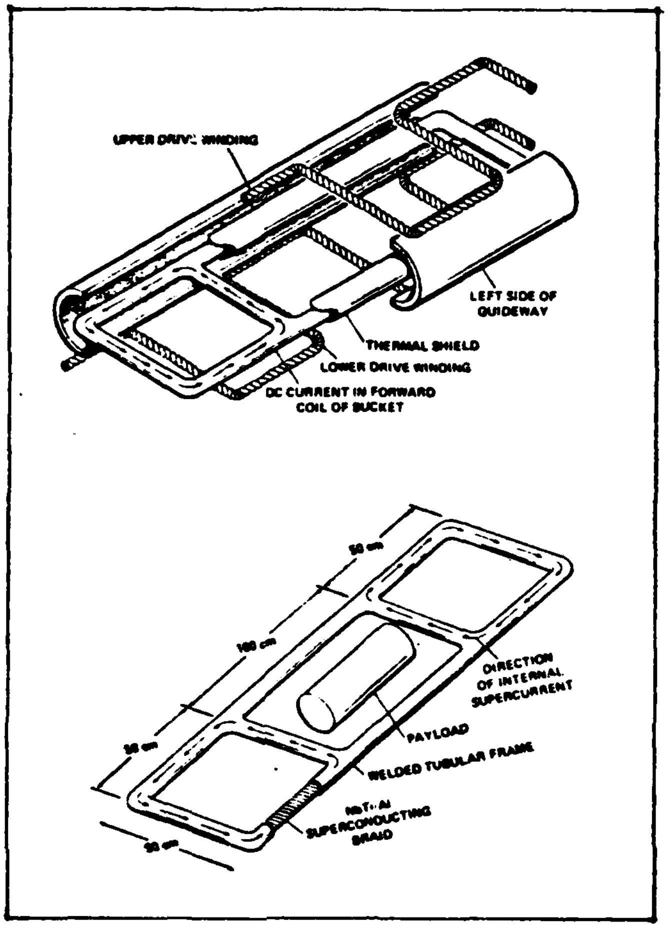


Figure 2.6 Mass Driver Planar Bucket Geometry (Ref 12: 42, 50)

One type of passive mass catcher (see Figure 2.7) is a large rotating conical structure which because of its size (100 m. in radius) is a good "target" for the mass driver. The packets of lunar material break up when they strike the front of the mass catcher which is a wire grid. The ore enters the mass catcher and is kept inside because of "centrifugal force". Dr. Heppenheimer in his book <u>Colonies in Space</u> suggests using these mass catchers as space ore carriers ("supertankers") which can haul hundreds of thousands of tons of lunar material to L5. These space ore carriers will use rotary pellet

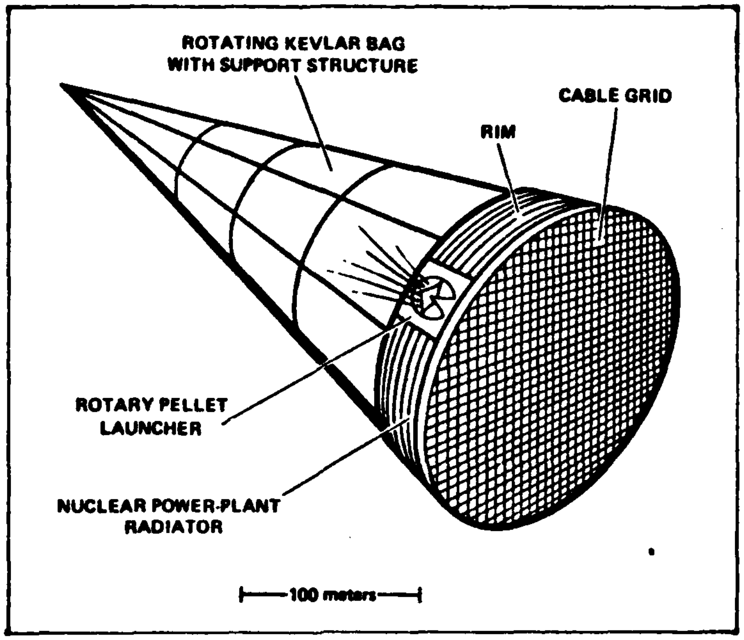


Figure 2.7 Passive Mass Catcher (Ref 11: 80)

launcher (RPL) (see Figure 2.8) as the propulsion device (see the above mentioned book for the description of the RPL) and will take many weeks to transit between L2 and L5. He assumes there will be several carriers in service at any given time with one mass catcher on duty at L2 at all times (Ref 24: 90-93).

An active mass catcher (see Figure 2.9) actively tracks a lunar ore packet and then positions itself to capture the packet. The mass catcher then slows the packet down and directs it to a storage area where the ore is loaded into an space ore carrier (Ref 11: 110). If the mass catcher is designed to intercept the packets of lunar material, intact, the fiberglass sacks could be used to store the lunar material in space prior to shipment to L5 (Ref 12: 128). This study assumes an active mass catcher as did the 1975 NASA-Ames Summer Study. The IOS is

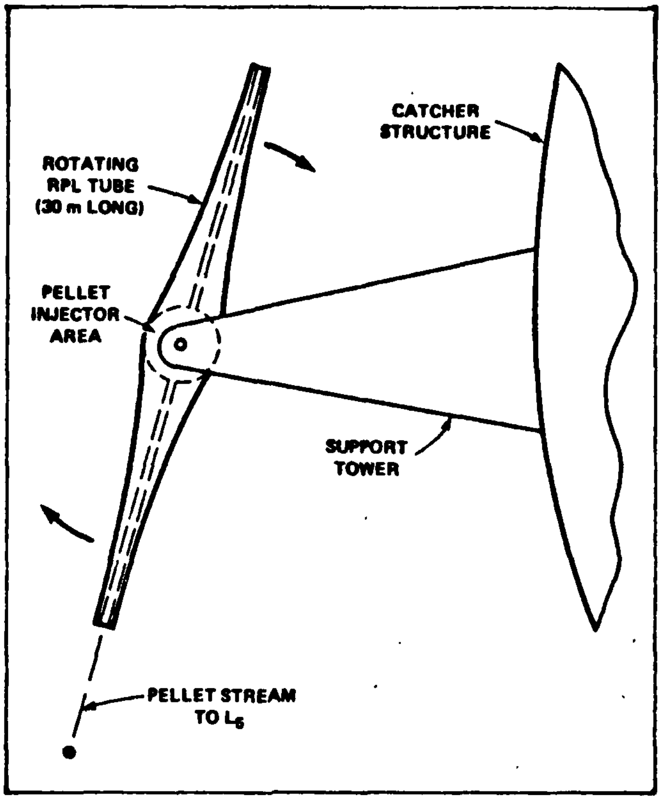


Figure 2.8 Rotary Pellet Launcher (Ref 11: 109)

utilized as the space ore carrier.

Stable Lagrangian Point Four (L4)

The SCMS will require a large space colony, with an approximate population of 10,000 people, at L4. The space colony will have the facilities to transform raw materials (processed lunar and asteroidal ore from L5) into new space colonies at L4 and parts for SSPS's which will be constructed at GEO. The space colony will also have the capability to unload, service (minimum), and load IOSs.

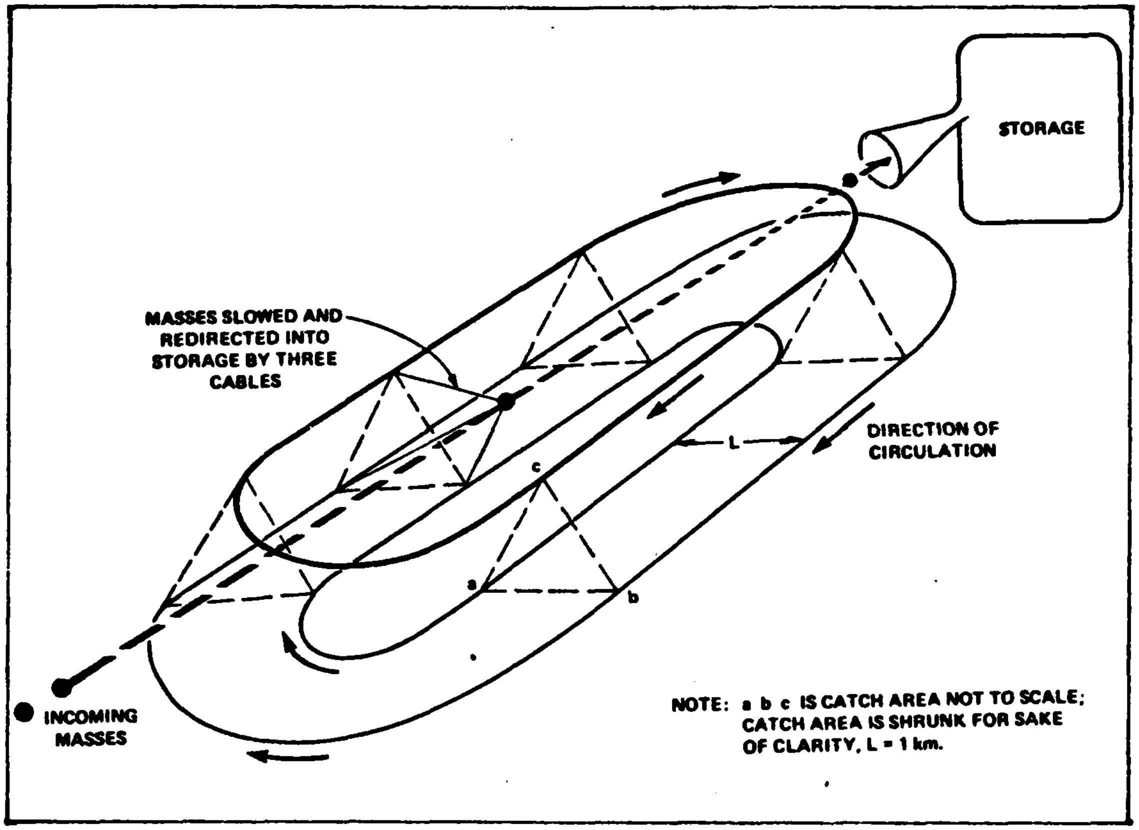


Figure 2.9 Active Mass Catcher (Ref 11: 109)

Space Colonies. In the literature, there are three major designs for a space colony. At first, Dr. O'Neill suggested using rotating cylinders with spherical endcaps as the space colony (see Figure 2.10). The space colony would consist of two cylinders connected by supporting structures and rotating in opposite directions. This counter-rotation would counteract the tendency of the colony to be inertially stable and allow the colony to track the Sun (Ref 5). In his book High Frontier, Dr. O'Neill suggested using the Bernal Sphere (see Figure 2.11), a rotating sphere, as the initial colony and moving to a large version of his rotating cylinder as the population increased (Ref 14).

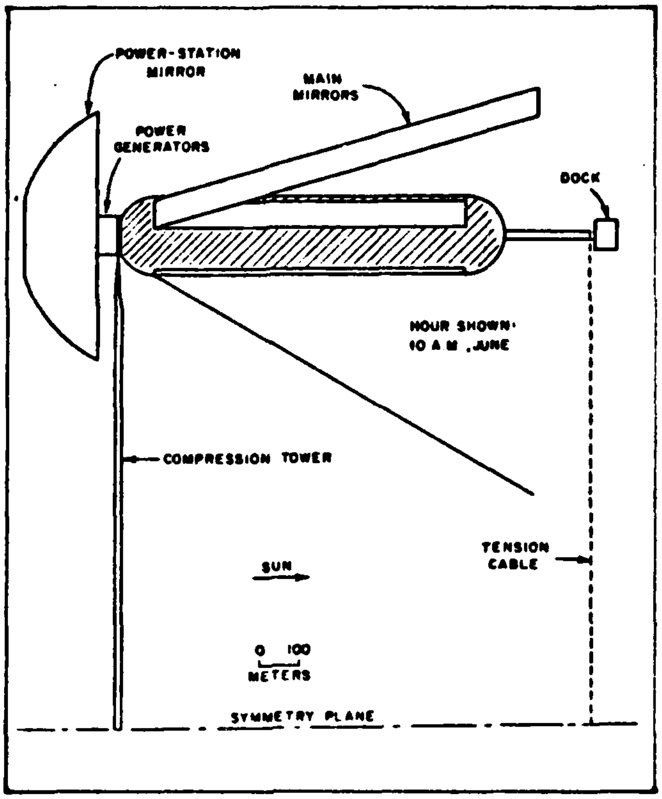


Figure 2.10 O'Neill's Cylindrical Space Colony (Ref 6: A-7)

Another space colony concept was the Stanford Torus (see Figure 2.12). This space colony, a rotating torus, was developed at the 1975 NASA-Ames Summer Study which was also co-sponsered by Stanford University for whom the space colony was named. The initial colony would cost around $190.8 billion with future colonies costing around $112.7 billion (Ref 11: 152-155).

The Stanford Torus would require a mass of approximately 750,000 metric tons which does not include the mass of a radiation sheild. The 1975 NASA-Ames Summer Study suggests using a passive radiation sheild to protect the inhabitants from cosmic rays. If this is done, a sheild of

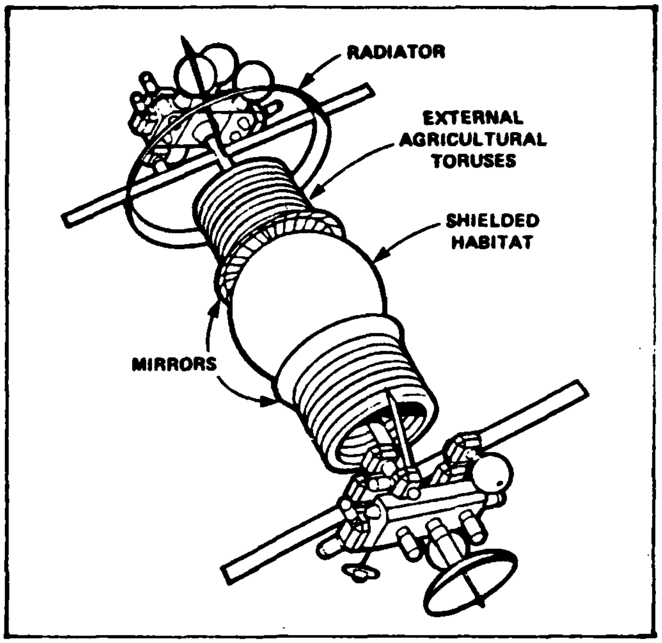


Figure 2.11 Bernal Sphere Space Colony (Ref 11: 48)

approximately 9,900,000 metric tons would be required (Ref 11). This study will use the Stanford Torus as the space colonies at L4 and L5. This study assumes that an active radiation sheild will be developed in the future so that the large amounts of mass are not needed.

Satellite Solar Power Station (SSPS).

> An important goal for the design foı space colonization is that it be commercially productive to an extent that it can attract capital. It is rather striking then that the study group has been able to envision only one major economic enterprise sufficiently grand to meet that goal. No substitute to the manufacture of solar power satellites was concieved, and although their manufacture is likely to be extremely valuable and attractive to investors on Earth, it is a definite weakness of the design to depend entirely on this one particular enterprise (Ref 11: 54).

This study also looks at the SSPS as its only product but it should be noted that selling metals to the Earth might also be a very profitable

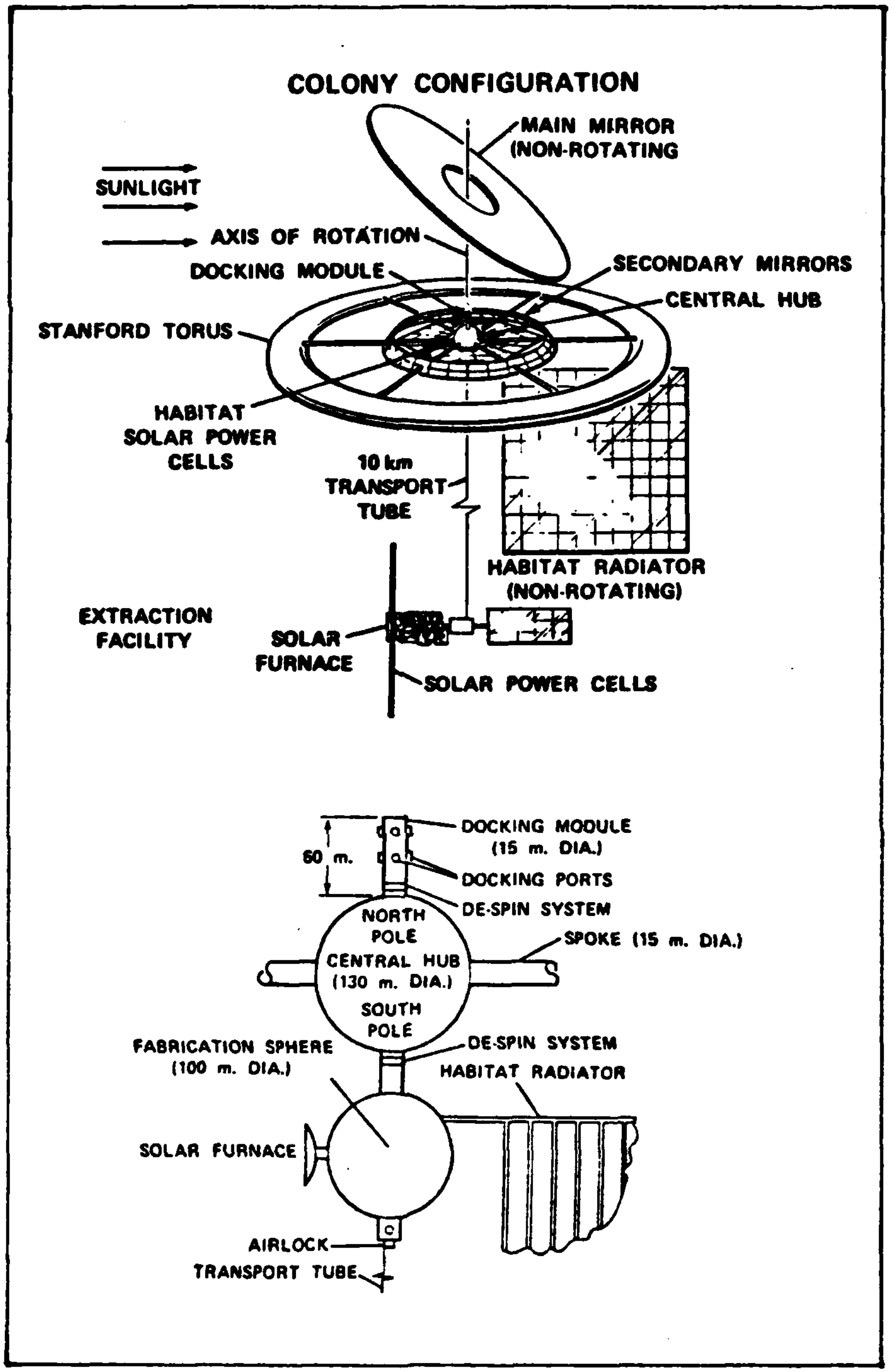


Figure 2.12 Stanford Torus Space Colony (Ref 24: 119-120)

enterprise. Since asteroidal steel is assumed to be better than any Earth steel, the merchandising of steel could be a profitable enterprise (Ref 6: 30).

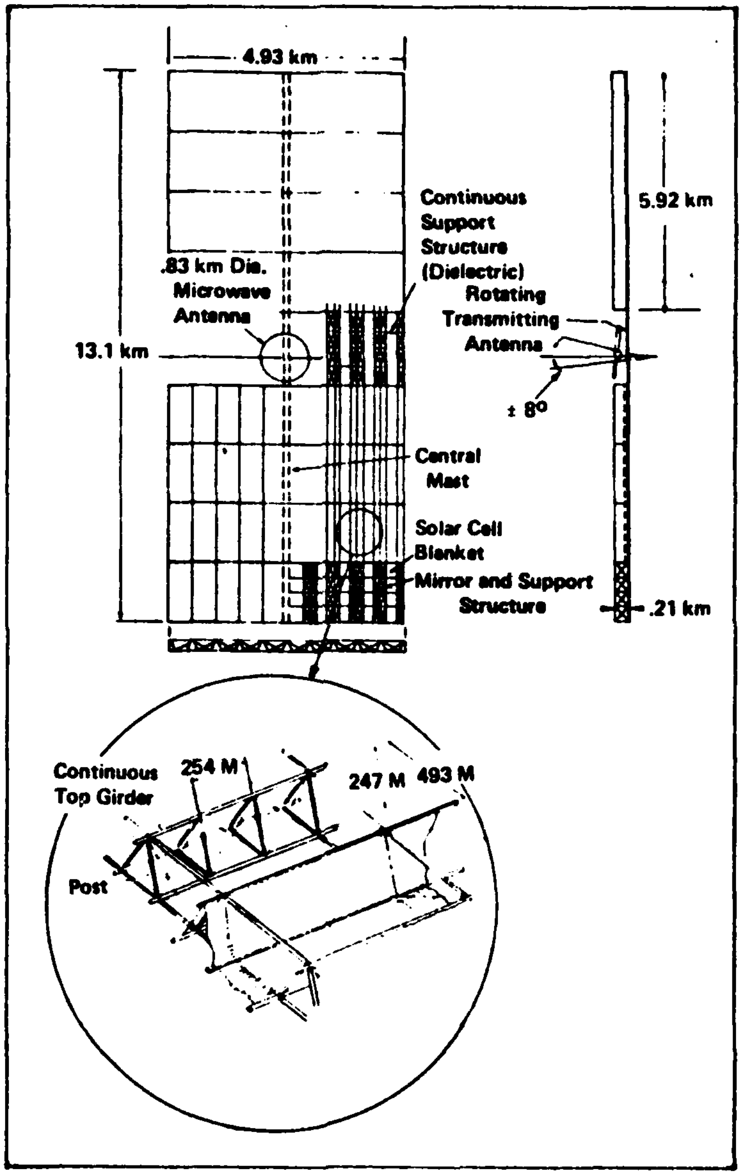


Figure 2.13 Satellite Solar Power Station (Ref 7: 118)

Two different types of SSPS have been considered for manufacture at the space colony. The first type is a SSPS which uses closed Brayton cycle turbines. This system uses the thermodynamic properties of a working fluid to produce the electricity (Ref 7: 129-133). The second type of SSPS (see Figure 2.13), a silicon solar cell based system, was designed by Peter Glaser. This study choose Glaser's SSPS for production at L4, as did most of the other studies. The characteristics of the SSPS (Ref 7: 115-128) are the following (prices in 1974 dollars):

1) Power = 5 GW.;
2) Mass = 39,960,000 lb. = 18,130,000 kg.;
3) Dimensions = 13.1 km. x 4.93 km. x 0.21 km.;
4) Operational lifetime = 30 years;
5) Output microwave frequency = 2.45 GHz.;
6) Cost of an SSPS = $7.6 million;
7) Price of electrical power on the Earth = 27.0 mils/kWh;
8) Expected life-cycle revenues per SSPS = $35 billion;
9) Operating costs for the SSPS = $140 million; and
10) Development costs for the entire SSPS program = $20 billion.

Stable Lagrangian Point Five (L5)

The SCMS will require a large space colony, with an approximate population of 10,000 people, at L5. The space colony will have the facilities to process lunar and asteroidal ore to recover the metals and non-metals required by the SCMS. The space colony will have the facilities to transform raw materials (processed lunar and asteroidal ore) into new space colonies at L5 and to prepare some of the raw materials for shipment to L4. The space colony will also have the capability to unload and load IOSs. The SCMS's IOS Repair Facility, where all major repairs on IOSs will be performed, will be located at L5.

Asteroids. To make a space colonization and manufacturing system approach any type of economic feasibility, the material for building space colonies and SSPS's must come from a location other than the Earth because of the high cost of transporting material from the Earth's surface into space. The most obvious source of the extraterrestial material is the Moon. While the Moon is a good choice, the Moon does not contain all the necessary metals and non-metals needed by the SCMS, that is, hydrogen for water and fuel and carbon for agriculture and chemical proceses.

To correct this deficiency, asteroidal material can be used to either supplement or eliminate the material from the Moon. While the exact composition of asteroids is not known, studies of meteorites and reflective spectroscopy of asteroids have given estimates of the asteroidal composition (Ref 25). Asteroids are catagorized into three basic types (Refs 26: 185-188):

1) Carbonaceous chondrites (CC), which are a particular type of stony meteorite, are approximately 20 percent iron, contain water and carbon, and constitutes about 80 percent of the asteroids;
2) Stony-irons are aproximately a 50/50 mixture of minerals and iron metal and constitutes about 10 percent of the asteroids; and
3) Irons, which are sometimes called nickel-irons (Ni-Fe) or

grouped in with the stony irons, are mostly iron but may contain 10 to 25 percent nickel and constitutes roughly the remaining 10 percent of the asteroids.

To use asteroidal ore in the SCMS, the ore must first be brought to L5. To accomplish this, an IPSV will be used to rendezvous and transport an asteroid back to L5. The 1977 NASA-Ames Summer Study describes a procedure in which a mass driver propelled space vehicle would rendezvous with an asteroid, de-spin the asteroid, place the asteroid into a large wire mesh net, and tow it back to the Earth-Moon system. On the return trip to the Earth-Moon system, the space vehicle would mine the asteroid, do enough processing of the asteroidal ore to retreive some of the valuable minerals, and use the waste products from the processor as fuel for the mass driver. Starting with a 1,000,000 metric ton asteroid, the space vehicle would return to the Earth-Moon system with approximately a 532,000 metric ton fragment. The round trip flight time for the IPSV would be about five years (Ref 13: 173-189). The model will use an asteroid with a returned mass of 525,000 metric tons arriving at L5 with an arrival rate of between 4.5 and 5.5 years.

Ore Processing Plant. Once the lunar and asteroidal ore arrives at L5, it must be processed to obtain the metals and non-metals (raw materials) needed by the SCMS. Since the lunar ore arrives at L5 already crushed there will be minimal problems injecting the ore directly into the processing system. The asteroidal material is another problem. .. arrives at L5 basicly as a 500,000 metric ton rock with the exception of the minerals processed on the IPSV's return trip. Therefore to process the ore, the asteroid will have to be mined to

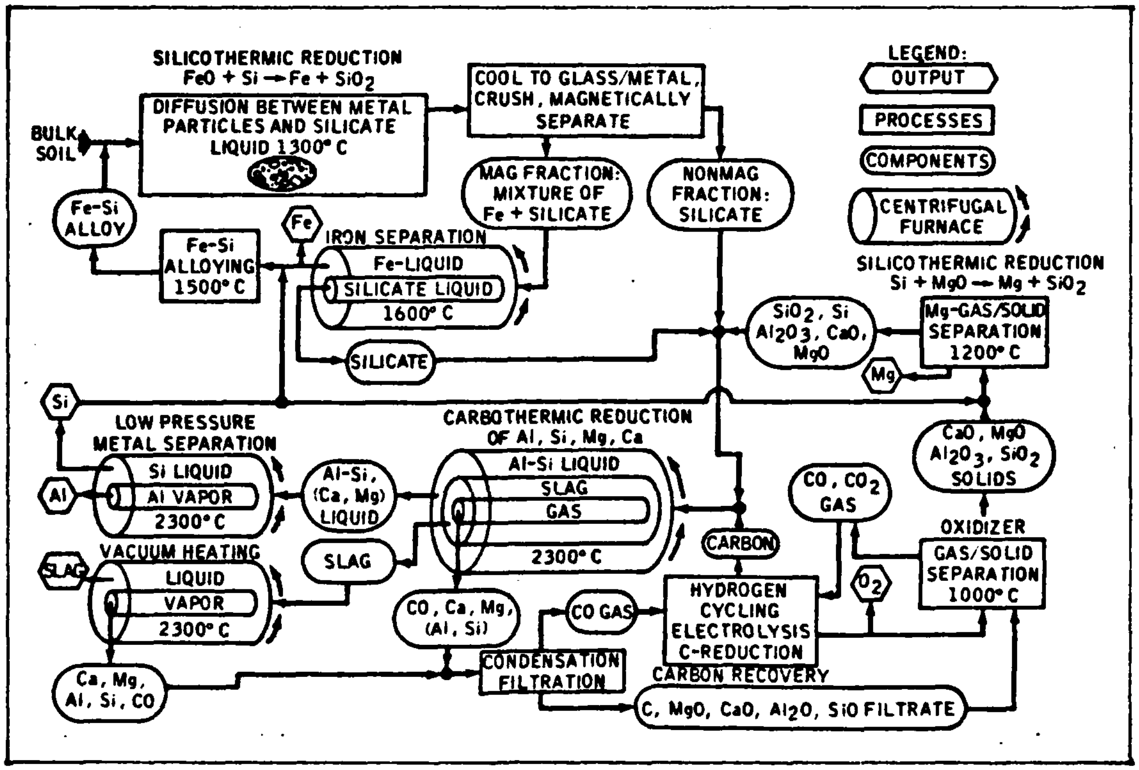


Figure 2.14 Lunar Ore Processing Plant (Ref 12: 107)

obtain the ore in a small enough size so the ore can be placed into the processing system. The space colony will therefore require a mining facility to mine the asteroid.

Once both the lunar and asteroidal ore are prepared, they must be processed. Several studies suggested possible processing schemes. Some schemes only considered lunar ore (Ref 12: 97-123); other schemes considered only asteroidal ore (Ref 6: A-51 - A-55); and, finally, some systems looked at processing both lunar and asteroidal ore (Ref 13: 257-274). Since the exact processing system will depend on the composition of the lunar soil and the asteroids and future improvements to process technology, choosing a particular processing system at this

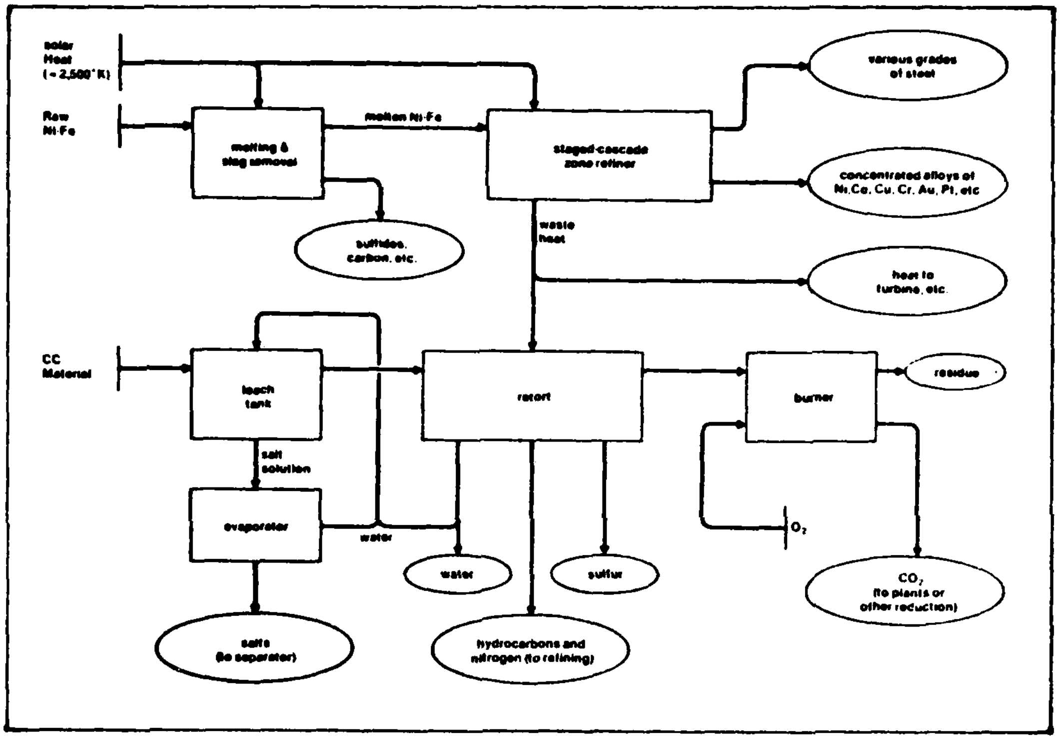


Figure 2.15 Asteroidal Ore Processing Plant (Ref 6: A-53)

time is difficult. Since the model developed in Chapter III does not depend on the particular processing system but on the process time, a particular process was not used but the lunar and asteroidal ore processing were seperated. Even though a particular system was not choosen, Figures 2.14 and 2.15 illustrate two possible processing systems: one for lunar ore and one for asteroidal ore.

Summary

A possible structure for a space colonization and manufacturing system was proposed in this chapter. The exact composition of this SCMS is conjecture and the structure was arbitrarily selected so as to present a possibly worst case, in terms of size and complexity, space colonization and manufacturing system. The system that will be developed in the future will probably have all the elements but the structure may be simplified. The next chapter will take the SCMS and develop a simulation model of it to determine what will be the sensitive points in the transportation system.

III. The Computer Model for the Transportation System of the SCMS

Introduction

Robert E. Shannon, in his book *Systems Simulation*, has defined simulation as the "process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various stratagies (within the limits imposed by a criterion or set of criterion) for the operation of the system [italics removed] (Ref 27: 2)." The program that will be described in this chapter can be used for both of these purposes. It can be used by a user to understand what is needed in a transportation system for a space colonization and manufacturing system and how a transportation system operates. The program can also be used to evaluate how a modification to the transportation system will affect the entire transportation system.

The process of building a simulation model is illustrated in Figure 3.1. As can be seen, the process is iterative with each step building on previous steps and also on future steps. The *Formulation of the Problem* was given in Chapter I along with the decision to use simulation. The *System Definition* was presented in Chapter II. The *Model Formulation*, *Data Preparation*, *Model Translation* and *Validation* will be presented in this chapter. The *Stategic Planning*, *Tactical Planning*, *Experimentation*, and *Interpretation* will be discussed in Chapter IV. The *Document* for the program is this report and the *Implementation* will be left up to the user.

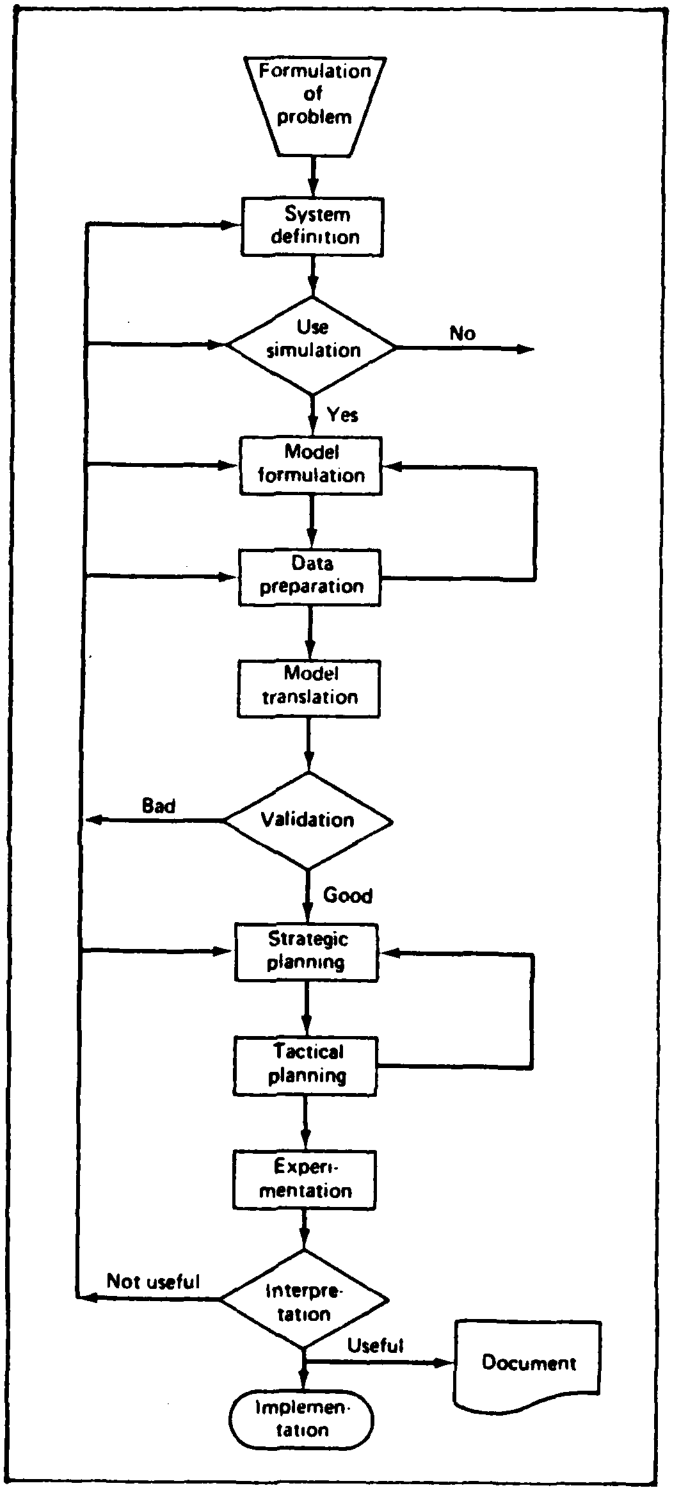


Figure 3.1 The Simulation Modeling Process (Ref 27: 24)

Model Formulation (Ref 26: 14-16)

Shannon defined a model as "a representation of an object, system, or idea in some form other than that of the entity itself (Ref 27: 4)." Most models have a combination of the following ingredients:

1) components,

2) parameters,

3) variables,

4) functional relationships,

5) constraints, and

6) criterion functions.

Components. Components are the parts, elements, or subsystems which make up the system under study. In this system, the components are the subsystems (LEO, GEO, LLO, L2, L4, and L5) of the SCMS and the elements which make up the subsystems, such as the unloading and loading docks and the service facilities.

Parameters. Parameters or modified control variables are quantities which can be modified by the user. The main parameters in the model are the probabilities used to determine branching in the Q-GERT network; the size of an IOS's cargo; and the masses of the space colonies, SSPSs, and asteroids.

Variables. Variables are quantities which can take on only those values that the form of the function allows. There are basically two major types of variables: exogeneous and endogeneous. Exogeneous or input variables originate or are produced outside of the system or result from extermal cause. Other names for the input variables are stochastic and independent variables. Endogeneous or dependent variables are referred to by two names depending on their use:

1) state or control variables which indicate the state or condition within the system, and
2) output or response variables which leave the system.

The input variables used in the model are the HLV, LLV, and mass driver launch rates and the arrival rate of asteroids. The status variables are the unloading, servicing, loading, travel, building, and processing times. The output variables are the number of IOSs, the number of new space colonies, the number of new SSPSs, the number of damaged/retired IOSs, the number of old/retired IOSs, and number/type of trips made by IOSs.

Functional Relationships. A functional relationship describes the relationship between variables and parameters to show their behavior within and/or between components of a system. The functional relationship used in this study is Queueing Theory (see Chapter I, "Methodology").

Constraints. "Constraints are limitations imposed on values of the variables or on the way in which resources can be allocated or expended. These constraints can either be self-imposed by the designer or system-imposed by the nature of the system (Ref 27: 16)." The self-imposed constraints in this system are the minimum and maximum values for the Q-GERT parameter sets, using only one server per activity, and using only one asteroidal miner. The system-imposed constraints are that an IOS or IPSV can travel only at speeds which are technologically feasible; the maximum launch rate for HLVs, LLVs, and mass drivers can be only as large as the capability of the launching facility; and that unloading, servicing, loading, building, and processing times can be only as small as technologically feasible.

Criterion Function. "The criterion function is an explicit statement of the objectives or goals of the system and how they are to be evaluated." The main criterion function for this study is to determine the optimum number of inter-orbit shuttles needed in the transportation system of the Space Colonization and Manufacturing System. Where "optimum" is defined as the number of IOSs needed to always have a ship to haul a cargo of raw materials from L5 to L4 while there are no excess IOSs or cargos at any other point in the system for an inordinate amount of time.

Data Preparation

The data needed by the model was obtained in two ways. The first was from books on the subject (Ref 5-16, 20-25) which gave estimates on travel times, masses, etc. The other method was estimates by the model designer. These estimates were on the probabilities used in branching and on the unloading, servicing, and loading times. The estimates for building and processing times were made by a combination of these methods. To obtain better results the user might have to obtain updated or possibly new estimates on all parameters and variables.

Model Translation

Described in this section is the computer simulation model for the transportation system of the Space Colonization and Manufacturing System (SCMS). The computer model was first developed as a six node transportation system for the SCMS. Each node was then developed as a multiple queueing system in which the IOSs were unloaded, serviced, and loaded; the space colonies and SSPSs were built; and lunar and asteroidal ore was processed. Each node in the transportation system will have the same names as the subsystems of the SCMS. For the rest of this section, the nodes of the transportation system will be called subsystems as was done in Chapter II. The term "node" will be used to refer to Q-GERT nodes. The subsystems of the transportation system are the following:

1) Low Earth Orbit (LEO),
2) Geostationary Earth Orbit (GEO),
3) Low Lunar Orbit (LLO),
4) Unstable Lagrangian Point Two (L2),
5) Stable Lagrangian Point Four (L4), and
6) Stable Lagrangian Point Five (L5).

Because of the lack of knowledge of the exact distribution for an activity time in the model (Activities), a uniform distribution for each activity time was assumed. Minimum and maximum values for each distribution were selected as described in the previous section. The proper values for these minimum and maximum values, the correct distributions, and the number of servers should be selected by the user based on his knowledge of:

1) the type of propulsion system that will be used in his model's IOSs,
2) the difficulty in loading and unloading an IOS,

3) how much time it takes to service an IOS,

4) the reliability of an IOS,

5) the time to build the space colony that will be used in his study,

6) the time to build SSPS parts and complete SSPSs that will be used in his study,

7) the processing scheme used to process lunar and asteroidal ore, and

8) the size of a cargo for an IOS.

To describe the computer model of the transportation system, the study will follow a hypothetical IOS as it travels to and through each subsystem in the system. Each subsystem will be described in terms of the elements which were given in Chapter II and the Q-GERT structures that were used to represent the model. A listing of the computer model/program is given in Appendix A with the Q-GERT nodal diagram given in Appendix B. A description of the Q-GERT structures used in this program given in terms of the nodal structure and the Q-GERT Analysis Program's input cards can be found in Ref 19.

Low Earth Orbit (LEO). An IOS will arrive at LEO (Node 1) loaded with a cargo of miscellaneous items. After arriving, the IOS will be unloaded (Node 2 and Activity 1) and then serviced (Node 4 and Activity 2). Next a decision (Node 5) will be made to determine if the IOS will go unloaded to L2 (Node 8), to provide extra ships for transporting lunar ore between L2 and L5, or to load (Node 6) the IOS with a cargo of miscellaneous items from the Earth for another destination in the SCMS. If the decision is to get a cargo from the Earth, the IOS will be placed in a waiting line (Node 7) to wait for the next HLV launch. (Decisions are based on probabilities which are stored in Attributes 5, 6, 7, and 8 of the IOS or the Transaction.)

The HLVs will be launched (Node 9) stochastically using a uniform distribution. Based on the size of the HLV, the size of the IOS, and how full the IOS will be when leaving LEO, LEO will prepare (Node 10) an IOS cargo which could be made up of multiple or fractional HLV cargos. After the cargo is prepared (Node 11), the cargo will be placed into storage (Node 12) to wait for the next IOS. When both the cargo and the IOS are at LEO, the cargo will be loaded (Node 13 and Activity 3) into the IOS and the IOS will be sent to another SCMS subsystem (Nodes 15-18) based on a probabilistic decision (Node 14). (Travel times between SCMS subsystems are determined by Attribute 4 of the IOS.)

Geostationary Earth Orbit (GEO). An IOS will arrive at GEO (Node 19) loaded with either a cargo of miscellaneous items (Node 20) or a cargo of SSPS parts (Node 23). (The type of cargo is determined by Attribute 3 of the IOS.) The IOS with a cargo of miscellaneous items will be unloaded at Unloading Dock No. 1 (Node 21 and Activity 4) and then head toward the service facility (Node 29). The IOS with a cargo of SSPS parts will be unloaded at Unloading Dock No. 2 (Node 24 and Activity 5) and head for the service facility (Node 29) after being seperated from the SSPS parts (Node 25).

All IOSs will be serviced (Node 30 and Activity 6) prior to the decision (Node 31) to have the IOS leave GEO either loaded (Node 32) or unloaded (Node 34). If the IOS leaves GEO unloaded, another decision (Node 34) will have to be made: Will the IOS go to L4 (Node 35) or L2 (Nod HI AWHH)H!';DH ich is to be loaded, will be loaded (Node 33 and

Activity 8) with a cargo of miscellaneous items and sent to another SCMS subsystem (Nodes 38-42) based on a probabalistic decision (Node 37). An assumption is made here that there will always be a cargo ready to be loaded.

The SSPS parts, after being unloaded from the IOS at Unloading Dock No. 2, will be placed in storage (Node 26) to await being installed on an SSPS (Activity 7). For the SSPS utilized in this study, it will take twelve IOS cargo loads of SSPS parts (18,000 metric tons) to have enough material to build a complete SSPS (Node 27) and will take approximately one year to do the construction. The completed SSPS will then be placed into service (Node 28) supplying the Earth with electrical power.

Low Lunar Orbit (LLO). An IOS will arrive at LLO (Node 42) loaded with a cargo of miscellaneous items. After arriving, the IOS will be unloaded (Node 43 and Activity 9) and then serviced (Node 45 and Activity 10). Next a decision (Node 46) will be made to determine if the IOS will go to L2 (Node 49) or to load (Node 47) the IOS with a cargo of miscellaneous items from the Moon for another destination in the SCMS. If the decision is to go to L2 then another decision (Node 49) will have to be made: Does the IOS go to L2 loaded (Node 50) or unloaded (Node 53). If the decision is to send the IOS loaded to L2, then the IOS will be loaded at Loading Dock No. 2 (Node 51 and Activity 12). If the decision is to get a cargo from the Moon, the IOS will be placed in a waiting line (Node 48) to wait for the next LLV launch.

The LLVs will be launched (Node 54) stochastically using a uniform distribution. Based on the size of the LLV, the size of the IOS, and how full the IOS will be when leaving LLO, LLO will prepare an IOS cargo which could be made up of multiple or fractional LLV cargos (Node 55). After the cargo is prepared (Node 56), the cargo will be placed into storage (Node 57) to wait for the next IOS. When both the cargo and the IOS are at LLO, the cargo will be loaded into the IOS at Loading Docl. No. 1 (Node 58 and Activity 11) and the IOS will be sent to another SCMS subsystem (Nodes 60-63) based on a probabilistic decision (Node 59).

Unstable Lagrangian Point Two (L2). An IOS will arrive at L2 (Node 64) either loaded (Node 65) with a cargo of miscellaneous items from LLO or unloaded (Node 68). (The status, loaded/unloaded, of an IOS is determined by Attribute 2 of the IOS.) The IOS with a cargo of miscellaneous items will be unloaded (Node 66 and Activity 13) and then head toward the service facility (Node 69) while the unloaded IOS will head directly to the service facility (Node 69).

All IOSs will be serviced (Node 70 and Activity 14) prior to making the decision (Node 71) to have the IOS leave L2 loaded with a cargo of miscellaneous items (Node 74) or a cargo of lunar ore (Node 72). If the decision is to send a cargo of miscellaneous items to LLO, then the IOS will be loaded at Loading Dock No. 2 (Node 75 and Activity 16) prior to being sent to LLO (Node 76). If the decision is to send a cargo of lunar ore to L5, the IOS will be placed in a waiting line (Node 73) to wait for the next complete cargo of lunar ore.

The lunar ore is sent to L2 by means of a mass driver (Node 77). The mass driver is assumed to launch approximately 105,000 metric tons of lunar ore per year to L2. This value is one-fifth of the mass of an asteroid and thus the Moon and an asteroid will supply approximately the same mass per year to L5. For a mass driver to launch this amount of mass in a year, the mass driver will have to launch a 20 kg. packet of lunar ore approximately once every six seconds. Because it would take 75,000 packets to fill the 1500 metric ton capacity IOS, the "packets" were redefined as a mass of 1500 metric tons which will be launched approximately once every 5.2 days.

The packets, which are launched stochastically by the mass driver (Node 77) using a uniform distribution, will be caught by a mass catcher (Node 78) located at L2. The packets will be prepared as a cargo for the IOS (Node 79) and then placed into storage (Node 80) to wait for the next IOS. When both the cargo and the IOS are at L2, the cargo will be loaded into the IOS at Loading Dock No. 1 (Node 81 and Activity 15) and the IOS will be sent to L5 (Node 82).

Stable Lagrangian Point Four (L4). An IOS will arrive at L4 (Node 83) either loaded (Node 85) or unloaded (Node 84). If the IOS is unloaded, it will head directly to the service facility (Node 92). If the IOS is loaded, it can have one of two types of cargos. An IOS with a cargo of miscellaneous items (Node 86) will be unloaded at Unloading Dock No. 1 (Node 87 and Activity 17) and then head to the service facility (Node 92). An IOS with a cargo of raw materials (Node 89) from L5 will be unloaded at Unloading Dock No. 2 (Node 90 and Activity 18) and then head for the service facility (Node 92) after being seperated (Node 91) from the raw materials.

All IOSs will be serviced (Node 93 and Activity 19) prior to making the decision (Node 103) of sending the IOS unloaded to L2 (Node 104) or sending the IOS loaded to another SCMS subsystem (Node 105). If the decision is to load the IOS, then another decision (Node 105) will have to be made: What type of cargo will be sent? If the cargo will be made up of miscellaneous items (Node 106), then the IOS will be loaded at Loading Dock No. 1 (Node 107 and Activity 20) (An assumption is made here that there will always be a cargo to be loaded.) and the IOS will be sent to another SCMS subsystem (Nodes 113-116) based on a probabalistic decision (Node 112). If the decision is to load the IOS with a cargo of SSPS parts (Node 108) for GEO, the IOS will be placed in a waiting line (Node 109) for the next cargo of SSPS parts.

Since the raw materials from L5 can be utilized in two fashions, a decision must be made to determine (Node 94) where the raw materials will be used. If the decision is to build SSPS parts (Node 95), the raw materials will be placed into storage (Node 96) to wait to be transformed (Activity 21) into SSPS parts which will be prepared (Node 97) as a cargo for an IOS and will be placed in storage (Node 98) to wait for the next IOS. When both the cargo and the IOS are at L4, the cargo will be loaded into the IOS at Loading Dock No. 2 (Node 110 and Activity 23) to be sent to GEO (Node 111).

If the decision is to use the raw materials in the construction of a new space colony (Node 99) at L4, the raw materials will be placed into storage (Node 100) to wait to be transformed (Activity 22) into part of the new space colony. For the space colony utilized in this study, it will take 500 IOS cargo laods of raw materials (750,000 metric tons) to have enough materials to build a complete space colony (Node 101) and it will take approximately ten years to do the construction. The completed space colony will then be placed into service (Node 102) to supply more living space for the colonists.

Stable Lagrangian Point Five (L5). An IOS will arrive at L5 (Node 117) loaded with either a cargo of miscellaneous items (Node 118) or a cargo of lunar ore (Node 121). An IOS with a cargo of miscellaneous items will be unloaded at Unloading Dock No. 1 (Node 119 and Activity 24) and then head toward the service facility (Node 124). An IOS with a cargo of lunar ore will be unloaded at Unloading Dock No. 2 (Node 122 and Activity 25) and head for the service facility (Node 124) after being seperated from the lunar ore.

Prior to servicing, all IOSs will be checked for their age (Node 124) and if an IOS is over ten years old, it will be retired (Node 125). If an IOS is less than ten years old, a decision (Node 126) will be made to determine if the IOS needs major repairs. If the IOS needs only normal/minor repairs (Node 127), it will be sent to Service Facility No. 1 (Node 128 and Activity 26). If the IOS needs major repairs (Node 130), another decision (Node 130) will have to be made: Is the IOS repairable? If the IOS is not repairable, it will be retired (Node 134). If the IOS is repairable, it will be sent to Service Facility No. 2 (Node 132 and Activity 27).

For all servicable IOSs, a decision (Node 155) will be made to determine if an IOS will go unloaded to L2 (Node 156) or get loaded with a cargo (Node 158). If the IOS is to be loaded, then another decision will have to be made: What type of cargo will leave L5? If the decision is to load the IOS with a cargo of miscellaneous items (Node 163), the IOS will be loaded at Loading Dock No. 2 (Node 164 and Activity 33) (An assumption is made here that there will always be a cargo to be loaded.) and sent to another SCMS subsystem (Nodes 166-169) based on a probabalistic decision (Node 165). If the decision is to load the IOS with a cargo of raw materials (Node 159) for L4, the IOS will be placed in a waiting line (Node 160) to wait for the next complete cargo of raw materials.

Asteroids arrive at L5 (Node 137) stochastically using a uniform distribution approximately once every five years. The asteroids are placed in storage (Node 138) until the miner (Node 140) is free. When the miner is free and an asteroid is in storage, the miner starts mining the asteroid at the Asteroid Miner (Node 141-142 and Activity 29) facility. As the asteroid is mined, 1500 metric ton chunks are sent to the processor (Node 143). An asteroid, which has a mass of approximately 525,000 metric tons, will take approximately five years to mine and process. Once the asteroid is mined, the miner is freed (Node 139).

After the lunar ore is separated from the IOS, it is sent to Processing Plant No. 1 to be processed while the asteroidal ore is sent to Processing Plant No. 2. Once the lunar or asteroidal ore is processed, a decision (Node 146) will be made to determine where the raw materials will be used. The raw materials can be used at L5, at L4, or as fuel, which is the slag from the processing plants, for the IPSV. If the decision is to send the raw materials to L4, the raw materials will be placed in storage (Node 153) to wait for the next IOS. When both the cargo and the IOS are at L5, the cargo will be loaded into the IOS at Loading Dock No. 1 (Node 161 and Activity 32) to be sent to L4 (Node 162).

If the decision is to use the raw materials in the construction of a new space colony (Node 148) at L5, the raw materials will be placed into storage (Node 149) to wait to be transformed (Activity 31) into part of the new space colony. For the space colony utilized in this study, it will take the equivalent of 500 IOS cargo laods of raw materials (750,000 metric tons) to have enough materials to build a complete space colony (Node 150) and it will take approximately ten years to do the construction. The completed space colony will then be placed into service (Node 151) to supply more living space for the colonists.

Initialization. The Q-GERT network is initialized by Node 170 which triggers five activities:

1) the arrival of the first HLV (Node 9),
2) the arrival of the first LLV (Node 54),
3) the arrival of the first mass driver packet (Node 77),
4) the arrival of the first IPSV (Node 137), and
5) the generation of the first five IOSs (Node 154).

Therefore, the initial conditions for the Q-GERT network are the following:

1) a HLV cargo at LEO,
2) no SSPS at GEO,
3) a LLV cargo at LLO,
4) a cargo of lunar ore at L2,
5) one space colony at L4,
6) an asteroid at L5,
7) one space colony at L5,
8) five IOS in the SCMS, and
9) all unloading docks, servicing facilities, loading docks,

a new space colony (Node 148) at L5, the raw materials will be placed into storage (Node 149) to wait to be transformed (Activity 31) into part of the new space colony. For the space colony utilized in this study, it will take the equivalent of 500 IOS cargo laods of raw materials (750,000 metric tons) to have enough materials to build a complete space colony (Node 150) and it will take approximately ten years to do the construction. The completed space colony will then be placed into service (Node 151) to supply more living space for the colonists

Initialization. The Q-GERT network is initialized by Node 178 which triggers five activities:

1) the arrival of the first HLV (Node 9),
2) the arrival of the first LLV (Node 54),
3) the arrival of the first mass driver packet (Node 77),
4) the arrival of the first IPSV (Node 137), and
5) the generation of the first five IOSs (Node 154).

Therefore, the initial conditions for the Q-GERT network are the following:

1) a HLV cargo at LEO,
2) no SSPS at GEO,
3) a LLV cargo at LLO,
4) a cargo of lunar ore at L2,
5) one space colony at L4,
6) an asteroid at L5,
7) one space colony at L5,
8) five IOS in the SCMS, and
9) all unloading docks, servicing facilities, loading docks,

processing plants, mining facilities except for the asteroid miner itself (Node 140), and storage facilities are empty, that is, all queues are empty and all servers are free.

<u>User Function and Subroutines</u>. Q-GERT allows the user to modify the Q-GERT network and produce user generated statistics by use of a user function and three user subroutines. The User Function (UF) is used by the user to interact with the Q-GERT network while it is executing and inject extra detail into the program. The User Subroutine (US) is virtually interchangable with the UF function. The User Input (UI) subroutine allows the user to modify a Q-GERT network prior to execution. The User Output (UO) subroutine allows the user to output user generated statistics at the completion of the Q-GERT run.

In this program, the UF function is used to do the following:

1) keep track of what has been happening in the simulation, that is, the activities of an IOS and the number of new colonies, new SSPSs, and asteroids;
2) provide travel times for the IOSs; and
3) provide the probabilities utilized by all nodes that branch on probabilities.

The US subroutine is used to determine if a new IOS is needed in the simulation and, if so, inject it into the network. The UI subroutine initializes all user generated constants and probabilities used in the program at the start of the first run of the Q-GERT network and zeroes out the shuttle related arrays and the production variables, such as the number of new colonies, new SSPSs, etc., prior to any Q-GERT run. The UO subroutine is used to output the shuttle related arrays and the production variables.

Validation (Ref 28: 13-33)

Because of the complexity of the model/computer program discussed in the previous sections, an approach to validation was needed. A "towards-validation" approach developed by Craig S. Ghelber and Charles A. Haley was selected. The concept is defined as the "documented evidence that a computerized model can provide users verifiable insight, within the model's domain of application, for the purpose of formulating analytical or decision-making inferences (Ref 28: 13-14)." Models with the following characteristics lend themselves to the use of the towards-validation approach:

1) the requirement to compare alternative information for policy decisions,
2) limited or nonexistent supporting data from real world system,
3) physical processes that require numerous variables to adequately describe their complexity, and
4) seperable subsystems whereby variables can be partitioned into convenient groups.

A four-phase approach achieves the towards-validation process:

1) conceptual,
2) verification,
3) credibility, and
4) confidence.

Conceptual. There are four parts to the conceptual phase:

1) a formal written statement of the intended application of the

model,

2) specification of the degree of accuracy desired,

3) description of assumptions and limitations, and

4) structural model or framework for design development.

The first two parts of the conceptual phase were provided in the "Problem," "Objectives," and "Scope" subsections of Chapter I. The assumptions and limitations were addressed in the Chapter I and further expanded in Chapter II and in the previous section of this chapter. A structural model is provided in the system description in Chapter II.

Verification. The verification phase is made up of four parts:

1) structured walk-through,

2) verification of technical physical processes,

3) simulation of predictable events, and

4) testing of stochastic events.

The structured walk-through and the simulation of predictable events were accomplished at the same time by running each subsystem of the SCMS independently with a predetermined flow of events to check out the network. The verification of technical physical processes is achieved because of the structured format of the Q-GERT language and through the structured walk-through which illustrated that the network was operating as modeled. Because the statistical distributions used in the model are intrinsic functions of the Q-GERT language, the testing of stochastic events was determined to be unnecessary since these distributions have been previously verified and validated.

Credibility. The credibility phase, which deals with the intuitive and statistical appeal of the model, is made up of two elements:

1) face validation,

2) sensitivity analysis.

Face validation is usually accomplished by having an expert in the field give his opinion on how well the model fits the real world. Face validation was accomplished in the System Definition phase. This is because most of the data used in developing the model was derived from books written by experts in the field.

A limited sensitivity analysis was accomplished. Based on a small number of sample runs, the size of the IOS's cargo and the HLV, LLV, and mass driver launch rates greatly affect the outcome of the model. For example if the mass driver launch rate is large and the IOS's cargo size is small, the system will "blow up" in that the capacity of the Q-GERT system will be exceeded. This happens because the mass driver will produce more cargos waiting at L2 faster than the IOSs can deplete the number of cargos. Another sensitive area in the model is the probabilities used for branching. Because of the many interactions between the subsystem of the SCMS, it is possible to change a probability in one subsystem and affect what happens in another subsystem. Because the model is sensitive to launch rates, probabilities, and maybe other parameters, the values given to these parameters must be analyzed very closely. If one of the parameters is changed, it may be necessary to modify other parameters to compensate for the change.

Confidence. The final phase in the towards-validation approach is the confidence phase. It consists of the following steps:

1) statistical comparison of modified simulation runs with related data,

2) examination of the cost-benifit of increasing information, and

3) full documatation of the towards-validation process.

Because there are presently no known space colonization systems in existance, real data cannot be obtained to do step 1. Even though the model is expressed in terms of a space colonization and manufacturing system, this system can be compared with any six "node" transportation system where two types of raw materials come from two different source locations. One type of raw materials is sent to a preprocessing or packaging facility (node 1) prior to being sent to the main processing facility (node 2). The second type of raw materials is sent directly to the processing facility (node 2) where it is preprocessed prior to being processed. At node 2, a product is produced for use at that location and some of the processed raw materials are prepared to be sent to a different location (node 3). At node 3, the raw materials are transformed into a product which is used at that site and into a components for a large structure which are sent to another location (node 4). At node 4, the parts are assembled into a product which is used at that location. Two other source locations supply finished goods to two of the nodes (nodes 5 and 6) of the transportation system which redistributes the goods to all other locations in the transportation system. All nodes have the capability to unload, service, and load the vehicle used in the transportation model.

This system is described because if an example of it is found in the real world then the model developed in this study can be tested as in step 1 of the confidence phase. A possible example could be found in this nation's trucking industry which displays the need to unload, service, and load trucks and moves all types of cargo between different locations.

Because the probability that a space colonization and manufacturing system will be built in the next few decades is small, the cost-benifit of increasing information is a purely academic question. The cost of information can only be justified in that the information could increase the understanding of space colonization systems. If in the future a faction of society decided that this information is useful, then more information could be collected to validate the model. The last step of the confidence phase is this document.

Conclusion. Although the model is fairly easy to verify, it is very difficult to validate because all of the assumptions made throughout the study. The use of the toward-validation approach validates the model as well as can be accomplished given of the lack of definitive data.

Summary

The simulation modeling process was described in this chapter. Four of the steps (Model Formulation, Data Preparation, Model Translation, and Validation) were discussed as they relate to the model developed in this study. An experimental design will be described in the next chapter.

IV. Model Experimentation

Introduction

As stated in the "Introduction" of chapter III, there are two ways to utilize a simulation model: to understand the behavior of the system modeled and to evaluate various strategies for system operation. There are many experimental methods to use with this model which correspond to the above ways to utilize the model, such as running the model with constant parameters and running the model several times while changing different parameters to see how they affect the model.

Both of these experimental strategies will be examined in this chapter mainly with respect to the following items (Ref 27: [illegible]-33):

1) Strategic Planning which concerns how to design an experiment that will yeild the desired information;
2) Tactical Planning which is concerned with trying to resolve the following problems:
    a) initial conditions as they affect equilibrium, and
    b) reducing the variance of the answer while minimizing the number of required samples;
3) Experimentation which is executing the experimental strategy; and
4) Interpretation of the results of the experiment.

Constant Parameters

Strategic Planning. The Strategic Planning was accomplished as the model was developed. Knowing the format and content of the Q-GERT Analysis Program, the user statistics were developed to provide additional information. This additional information was assumed to provide the eventual user with all the data that would be needed to understand how the model operated.

Tactical Planning. The *Tactical Planning* was accomplished mainly by stating the initial conditions for the model (see Chapter III, "Model Translation"). A complete sensitivity analysis on the initial conditions was not done, so it should be accomplished in the future for the parameters choosen.

Experimemtation. The *Experimentation* consisted of running the program many times while changing the values of the parameters and variables to get an optimum solution. An optimum solution was defined in the "Criterion Function" subsection of the previous chapter.

This experimental strategy differs from the next one to be discussed in that, after an optimal solution is found, the parameters and variables are left alone. How the soluion differs from one run to the next is not a concern of this strategy except where it tells how to change a parameter to get the solution toward the optimum.

Interpretation. The computer model in Appendix A was run for a simulation time of 50 years. The solution analyzed in this section was not optimum since there were cargos staying at L2 longer than was considered appropriate. It could still be considered optimum in the sense that a IOS was always available at L5 for hauling a cargo of raw materials to L4. The solution could be improved by careful modification of the appropriate probabilities. This basic trial and error approach to optimization is necessary because of the amount of interaction between subsystems in the SCMS.

The program outputs information about the activities of each IOS, such as:

1) the number of trips between and to any subsystem,

2) the type of cargo hauled,

3) the age of an IOS,

4) the number of major repairs done on an IOS at L5, and

5) the fact that a IOS is retired and why.

The program also outputs summary data which is displayed in Table III.

Is it cost effective to separate the tasks of processing lunar and asteroidal ore from the production of SSPS? Based on the number of space colonies built it is possible to do a very simple cost effectiveness analysis. This analysis does not take into account many of the costs associated with a space colonization and manufacturing system because there are presently no cost estimates on them. Table IV presents the data and as can be seen the SCMS is cost effective using only these two sources of cost. To be able to answer the question about cost effectiveness accurately, cost information on the development costs, production costs, and operating costs of IOSs, HLVs, LLVs, and IPSVs must be determined.

Changing Parameters

This experimental strategy depends on what operational strategies

TABLE III

Summary Data for Simulation Model

During the 50.00 years investigated in this study the following happened:

Starting with one colony at L4 and one at L5 and no SSPS's at GEO, the following were built:

4 colonies at L4
4 colonies at L5
49 SSPSs at GEO

Total number of shuttles (1500 metric tons) is 428

Total number of trips that were made by all shuttles is 16693

Total number of major repairs that were done on all shuttles is 229

Total number of shuttles that were damaged beyond repair is 20

Total number of shuttles that were retired because of old age is 257

Average number of trips per year is 333.86000

The total number of asteroids retrieved for minning is 11

The total mass of asteroidal ore mined at L5 is 5775000 metric tons

The total number of lunar ore trips to L5 is 3273

The total mass of lunar ore sent to L5 is 4909500 metric tons

TABLE IV

Cost Effectiveness Analysis

Cost of one colony	$112.7 billion
Cost of 4 space colonies at L4	$450.8 billion
Cost of 4 space colonies at L5	$450.8 billion
Total cost of space colonies	$901.6 billion
Cost of a SSPS	$7.6 million
Cost of 49 SSPSs	$3.7 billion
Developmental cost of SSPS program	$20.0 billion
Operating costs for an SSPS for one year	$140.0 million
Total operating costs for 49 SSPSs (over a 30 year life-cycle for each SSPS)	$205.8 billion
Total cost of SSPSs	$229.5 billion
Total cost of space colonies and SSPSs	$1131.1 billion
Expected life-cycle revenues for each SSPS (over a 30 year period)	$35.0 billion
Total revenues for 49 SSPSs (over a 30 year period for each SSPS)	$1715.0 billion
Total profit (over a 80 year period)	$583.9 billion

the analyst will examine. A possible experimental strategy will be described but this is only one of many possible experimental designs. If more detailed information on experimental design is needed, the reader should review any good book on the subject such as Probability and Statistics in Engineering and Management Science by William W. Hines and Douglas C. Montgomery (Ref 29).

Strategic Planning. The Strategic Planning for this experimental strategy is the same as for the previous experimental strategy. Hopefully, all required information needed by the analyst is included in either the normal output or the Q-GERT Analysis Program or the user generated statistics provided by the model. If these are not sufficient, the analyst will have to modify the program to obtain the required information.

Tactical Planning. The Tactical Planning consists of a three-step process (Ref 27: 151):

1) determine the experimental design criteria,
2) synthesize the experimental model, and
3) compare model to standard experimental designs and choose the optimal design.

This phase can also be defined as (Ref 27: 150-161):

1) the design of the structural model which consists of:
    a) the number of factors, and
    b) the number of levels of each factor;
2) the design of the functional model which consists of:
    a) the number of data points used (the maximum number of data points is the product of the factors and levels),

and

b) the number of replications;

3) the design of the experimental model consists of the description of the standard experimental design or of the experimental design designed by the analyst.

Experimentation. The Experimentation will be left up to the user.

Interpretation. The Interpretation will be left up to the user.

Possible Experimental Design. A possible design is to examine how changing two different parameters or variables in the model affect the output (the number of IOSs) of the model. For this experimental design it is assumed that:

1) each parameter has only two allowable values,

2) all possible combinations of factors and levels will be used, and

3) at least the minimum number of replications will be used which will allow the interactions to be examined (this is two replications).

Therefore, a description of an experimental design would look like this:

1) the structural model:

a) the number of factors = 2, and

b) the number of levels of each factor = 2;

2) the functional model:

a) the number of data points = 4, and

b) the number of replications = 3;

3) the experimental model: A Two-Way Anova utiizing the Duncan Multiple Range Test for interactions.

The exact structure of the Two-Way Anova and the Duncan Multiple Range Test is given in Ref 29. The procedure to run the experiment and the assumptions which pertain are also described in Ref 29.

Summary

Described in this chapter are two possible experimental designs for analyzing the output from the computer model. Each of these designs serve to demonstrate the two ways to use a simulation model. Presented in the next chapter are a summary of the findings of the study and some recommendations for further research.

V. Summary, Recommendations, and Conclusions

Introduction

Described in this study is the development of a computer model of a transportation system for the Space Colonization and Manufacturing System (SCMS). Presented in Chapter I is the description of the history and current status of other proposed transportation systems for space colonization; the statement of the problem, research questions, objectives, and scope addressed in this study, and the description of an approach or methodology for the development of the computer model.

The system description was given in Chapter II while the description of the computer model was given in Chapter III with an attempt at verifying/validating the model using the towards-validation approach. Described in Chapter IV are two possible experimental designs with one design being illustrated by an example. Presented in this chapter is a summary of the finding derived from examination of the simulation model developed in this study and the results of the model. Also presented are some recommendations for future research.

Summary

The research questions and objectives presented in Chapter I have all been addressed in this study and have been answered to some extent in the preceeding chapters. How many IOSs are needed? Is the SCMS cost effective? While answers to these questions are nice to know, the answers derived from this model will only be gross estimates because of the lack of detailed information on space colonization and manufacturing systems. The main purpose of this study was not to answer these types of questions now but to develop a methodology which could be used in the future to answer these questions when more detailed information becomes available. The use of the Q-GERT network approach can show the user interactions between subsystems that the user did not know existed. Even if these interactions are not discovered, the process of converting the systems description for the user's space colonization and manufacturing system into a Q-GERT network forces the user to think about the system and, therefore, the user might discover some aspects of the system that were not included in the initial systems description.

The use of branching on probabilities caused many problems in the development of this computer program. Because of the lack of knowledge on these probabilities, they had to be estimated and then modified to produce the solution to the model described in Chapter IV. If, instead of using probabilities to do the branching, a user function was developed to determine the branching strategy, then it would be possible to include more decision making processes in the model. An example of where this would be useful is when a IOS must determine what type of cargo to be loaded. By using probabilities, there is a possibility that an IOS will be sent to a loading dock which has no cargos and possibly excess IOSs while another loading dock has excess cargos. By using attributes and a user function to determine the values of the attribute, the IOS can look ahead to determine which loading dock has cargo and branch accordingly.

While the number of unloading docks, service facilities, and loading docks was determined to coincide with the types of cargo or service, it is possible to merge some of these facilities to make a more compact system. While the number of servers at each facility was assumed to be one, it is possible to have more than one server and thus increase the production rate while decreasing the total time that the facility is busy.

Based on the information presented in this section and previous chapters, there are many recommendations for future research that could be presented. The next section gives only a few of these recommendations.

Recommendations for Future Research

During the development of this study, many problems were uncovered concerning the quality and quantity of present information on the parameters associated with transportation models for space colonization and manufacturing systems. The main rroblem was that there are very few, if any, good estimates published about the details of building space colonies, building SSPSs, or processing lunar or asteroidal ore. Basically only very gross estimates have been published. Because of the lack of better information, the gross estimates about process times and masses were used in this study. Therefore, the first recommendation is that some research should be done to determine the value or range of values that these parameters can assume. This cold be done by using the Delphi technique (Ref 30: 170-176) and experts in the field such as Gerard K. O'Neill and Thomas A. Heppenhiemer. (An example of a Delphi for a space problem is given in Ref 8.) Some of the parameters needing better, or even new, estimates are the following:

1) the size of a cargo for an IOS;
2) the type of propulsion system and, therefore, the flight times of an IOS;
3) the construction time for space colonies, complete SSPSs, and SSPS parts;
4) the processing and mining times for asteroidal ore;
5) the processing time for lunar ore;
6) IOS cargo preparation time;
7) unloading, servicing, and loading times for an IOS;
8) launch rates/arrival times for the HLV, the LLV, and the mass driver;
9) the masses and elemental composition of space colonies and SSPSs;
10) the elemental composition of lunar and asteroidal ore;
11) the mass of an active or passive radiation shield; and
12) the cost associated with the designing, building, and operating space colonies, SSPSs, IOSs, HLVs, LLVs, IPSVs, and mass drivers.

A second recommendation is to canvas the space colonization theoreticians to determine what components are needed to be added to or to be deleted from the transportation model discussed in this study. This could be accomplished using the Delphi technique discussed above.

A third recommendation is to modify the computer model to branch on attributes derived from a user function instead of on probabilities. This could be accomplished by having a user function that looks at cargo storage queues to see which ones have cargo and then having the IOS branch accordingly. Some branching on probabilities will still be needed to determine the destination of a loaded IOS.

At the present time if the user needs to modify the Q-GERT network or the user generated variables, the user must change the Q-GERT or FORTRAN code which is given in Appendix A. Therefore, the fourth recommendation is to modify the User Input subroutine to allow the user the option of modifying the Q-GERT network using data input cards. The program been written to allow this modification:

1) Each parameter set is used only with one activity.
2) The probability array elements are completely described to allow the user to know what is being modified.
3) All other user defined variables are adequately described so the user knows thier exact function.
4) Q-GERT has functions and subroutines which allow the modification of parameter sets, nodal descriptions, and activity descriptions (see Ref 19).

The final recommendation is after doing all/some/none of the other recommendations, the researcher should do a very thorough sensitivity analysis to determine how the following affect the model:

1) changing the probabilities for any particular node which branches on probabilities,
2) changing the times in the parameter sets such as travel times,
3) changing the amount of mass needed to build a space colony or an SSPS (the building times might also have to be changed),
4) changing the size/mass of the cargo for an IOS, and

5) changing the launch/arrival rates of the HLVs, the LLVs, the ISPVs, and the mass driver (the mass of the asteroid might also have to be changed).

As was stated before these are only some of the recommendations for further research. A bright researcher should be able to think up many more.

Conclusion

In conclusion, the main objective of this research was accomplished. A methodolgy for analyzing a large transportation model for a space colonization and manufacturing system was developed. By using the Q-GERT network approach allows the user to see how a real system might possibly operate. It allows the user to see what further information is needed to be collected to give better estimates on the system. The recommendations for future research have emphasised this latter aspect. Finally, the methodology developed in this study could be used with almost any large transportation systems either in space, on the ground, or a combination of both.

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AD-A124 685 A TRANSPORTATION MODEL FOR A SPACE COLONIZATION AND MANUFACTURING SYSTEM:..(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI.. L A WAGNER 2/2

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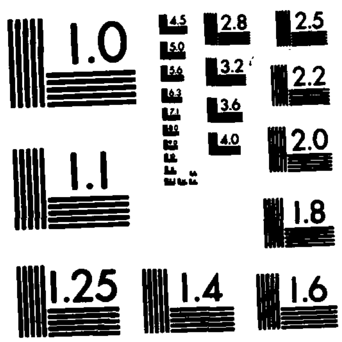

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APPENDIX A

The SCMS Computer Program Listing

The following program models the transportation system for the Space Colonization and Maunufacturing System (SCMS). The program is written in Q-Gert, a simulation language whose source code is written in ANSI standard FORTRAN 66. The user function and subroutines (UF, US, UI, and UO) are written in the CDC Cyber implemention of FORTRAN IV and uses several seven character variable names which might have to be modified to six or less characters to work in other implementations of FORTRAN IV. With these name changes, the program should work under both ANSI standard FORTRAN 66 and ANSI standard FORTRAN 77. Depending on the computer system on which the user will be running this program, the control cards might have to be modified to correspond to the new operating system's job control language.

```
LAW,CM377000,T600,I0600.  T820758,WAGNER,4293.
ATTACH,PROCFIL,QGERTPROC,ID=T800679.
FTN.
BEGIN,QGERT,PROCFIL,VER=4,MODE=X,M=LGO,PL=9999,PMD=ON.
*EOR
      FUNCTION UF(IFN)
C
C
C
C UF                   THE Q-GERT USER FUNCTION (UF) IS TO PROVIDE THE USER
C                      THE CAPABILITY TO INJECT EXTRA DETAIL INTO THE Q-GERT
C                      PROGRAM.  THE UF FUNCTION IN THIS PROGRAM IS USED
C                      MAINLY TO KEEP TRACK OF WHAT HAS BEEN HAPPENING IN
C                      THE SIMULATION (I.E., THE ACTIVITIES OF AN INTER-
C                      ORBIT SHUTTLE AND THE NUMBER OF NEW COLONIES, NEW
C                      SSPS'S, AND ASTEROIDS), PROVIDE TRAVEL TIMES FOR THE
C                      INTER-ORBIT SHUTTLES, AND THE PROBABILITIES UTILIZED
C                      BY ALL NODES THAT BRANCH ON PROBABILITIES.  UF IS
C                      ALSO THE VARIABLE WHICH STORES THE VALUE/RESULT OF
C                      THE UF FUNCTION.
C
C IFN                  THE USER FUNCTION NUMBER (IFN) TELLS WHAT PART OF THE
C                      FUNCTION THAT WILL BE PROCESSED.
C
C
C
      COMMON /QVAR/ NDE,NFTBU(500),NREL(500),NRELP(500),NREL2(500),
     1              NRUN,NRUNS,NTC(500),PARAM(100,4),TBEG,TNOW
C
C
C NDE                  NUMBER OF ATTRIBUTES ASSOCIATED WITH A TRANSACTION
C
C NFTBU(500)           ARRAY WHICH CONTAINS THE NODE NUMBER AT WHICH
C                      STATISTICS COLLECTION, VALUE ASSIGNMENTS, AND
C                      BRANCHING OCCUR WHEN A NODE IS RELEASED
C
C NREL(500)            ARRAY WHICH CONTAINS CURRENT NUMBER OF TRANSACTIONS
C                      IN A Q-NODE, NUMERIC QUEUE SELECTION CODE FOR S-NODE,
C                      OR THE NUMBER OF REMAINING INCOMING TRANSACTIONS
C                      REQUIRED TO RELEASE A NODE
C
C NRELP(500)           ARRAY WHICH CONTAINS INITIAL NUMBER OF TRANSACTIONS
C                      IN A Q-NODE, NUMERIC QUEUE SELECTION CODE FOR S-NODE,
C                      OR THE NUMBER OF TRANSACTIONS REQUIRED FOR FIRST
C                      RELEASE OF A NODE
C
C NREL2(500)           ARRAY WHICH CONTAINS MAXIMUM NUMBER OF TRANSACTIONS
C                      IN A Q-NODE, NUMERIC SERVER SELECTION CODE FOR
C                      S-NODE, OR THE NUMBER OF TRANSACTIONS REQUIRED FOR
C                      SUBSEQUENT RELEASES OF A NODE
C
C NRUN                 CURRENT RUN NUMBER
C
C NRUNS                TOTAL NUMBER OF RUNS REQUESTED
```

```
C
C NTC(500)         THE NUMBER OF TRANSACTIONS THAT HAVE PASSED THROUGH A
C                  NODE SINCE TBEG
C
C PARAM(100,4)     ARRAY WHICH CONTAINS THE PARAMETER SETS USED IN THE
C                  SIMULATION
C
C TBEG             TIME AT WHICH DATA COLLECTION IS TO BEGIN
C
C TNOW             CURRENT SIMULATION TIME
C
C
      REAL AGE,ATT(10),AVERAGE,LIFE,PROB(19,4),SHIP(1500,2),WEIGHT,
     1     YEAR,YEARS
C
      INTEGER ACTIVE,ASTER,L4COLON,L5COLON,MAXSHIP,NODE,QNODE,SHIPNO,
     1        SHUTTLE(1500,35),SIZE,SSPS,TOTAL(14)
C
      COMMON /INFO/ ACTIVE,AGE,ASTER,ATT,AVERAGE,LIFE,L4COLON,L5COLON,
     1              MAXSHIP,NODE,PROB,QNODE,SHIP,SHIPNO,SHUTTLE,SIZE,
     2              SSPS,TOTAL,WEIGHT,YEAR,YEARS
C
C
C
C ACTIVE           THE ELEMENT IN THE SHUTTLE ARRAY THAT INDICATES IF
C                  THE SHUTTLE IS OR HAS BEEN ACTIVE DURING THE
C                  SIMULATION
C
C AGE              AGE/LIFETIME IN YEARS OF A SHUTTLE
C
C ASTER            THE NUMBER OF ASTEROIDS THAT ARRIVE AT L5
C
C ATT(10)          ARRAY WHICH IS USED TO TEMPORARILY STORE THE
C                  ATTRIBUTES ASSOCIATED WITH A TRANSACTION
C
C AVERAGE          NUMBER OF TRIPS PER YEAR FOR A SHUTTLE WHILE IT IS
C                  STILL ACTIVE OR THE NUMBER OF TRIPS PER YEAR FOR ALL
C                  SHUTTLES FOR THE ENTIRE SIMULATION TIME
C
C LIFE             THE NORMAL LIFETIME OF A SHUTTLE
C
C L4COLON          THE NUMBER OF NEW COLONIES BUILT AT LAGRANGIAN POINT
C                  FOUR (L4)
C
C L5COLON          THE NUMBER OF NEW COLONIES BUILT AT LAGRANGIAN POINT
C                  FIVE (L5)
C
C MAXSHIP          THE MAXIMUM NUMBER OF SHUTTLES ASSUMED FOR THE
C                  SIMULATION
C
C NODE             THE Q-GERT NODE WHERE NEW SHUTTLES ARE BROUGHT INTO
C                  THE SYSTEM
C
C PROB(19,4)       ARRAY WHICH CONTAINS THE PROBABILITIES USED IN
```

```
C                    BRANCHING IN THE Q-GERT MODEL
C
C QNODE              THE Q-NODE WHERE SHIPS WAIT FOR A RAW MATERIALS CARGO
C                    TO GO TO L4
C
C SHIP(1500,2)       ARRAY WHICH CONTAINS THE TIMES THAT A SHUTTLE IS
C                    BROUGHT INTO THE SYSTEM AND IS RETIRED FROM THE
C                    SYSTEM
C
C SHIPNO             INDEX USED TO KEEP TRACK OF THE NEXT SHUTTLE NUMBER
C                    TO BE USED BY THE SYSTEM
C
C SHUTTLE(1500,35) ARRAY WHICH CONTAINS DATA ABOUT THE ACTIVITIES OF A
C                    SHUTTLE
C
C SIZE               THE CARGO SIZE (IN METRIC TONS) OF A INTER-ORBIT
C                    SHUTTLE
C
C SSPS               NUMBER OF SATELLITE SOLAR POWER STATIONS (SSPS) BUILT
C                    AT GEOSTATIONARY EARTH ORBIT (GEO)
C
C TOTAL(14)          ARRAY WHICH IS USED TO TEMPORARILY STORE CUMULATIVE
C                    STATISTICS ABOUT SHUTTLES
C
C WEIGHT             THE NUMBER OF "SIZE" METRIC TON UNITS (OR THE NUMBER
C                    OF SHIP LOADS) IN AN ASTEROID
C
C YEAR               NUMBER OF DAYS IN A YEAR
C
C YEARS              NUMBER OF YEARS IN THE SIMULATION
C
C I, J, AND K        TEMPORARY INDICES INTO ARRAYS
C
C
C
C GO TO THE PROPER ROUTINE BASED ON THE IFN
      GO TO (1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,
     1       1,1,1,1,1,2,3,4,5,6,7,7,7,7,7,7,7,7,7,7,7,7,7,7,7,7,7,7,7,
     2       8) IFN
C
C
C INCREMENT THE NUMBER OF TIMES A SHIP DOES SOMETHING (IFN = 1 TO 34)
C
C LOW EARTH ORBIT (LEO)
C
C SHUTTLE TRAVELS FROM LEO TO GEO -- LOADED                  (IFN = 1)
C SHUTTLE TRAVELS FROM LEO TO L5  -- LOADED                  (IFN = 2)
C SHUTTLE TRAVELS FROM LEO TO L4  -- LOADED                  (IFN = 3)
C SHUTTLE TRAVELS FROM LEO TO LLO -- LOADED                  (IFN = 4)
C SHUTTLE TRAVELS FROM LEO TO L2  -- UNLOADED                (IFN = 5)
C
C GEOSTATIONARY EARTH ORBIT (GEO)
C
C SHUTTLE TRAVELS FROM GEO TO LEO -- LOADED                  (IFN = 6)
```

```
C SHUTTLE TRAVELS FROM GEO TO L5  -- LOADED                    (IFN = 7)
C SHUTTLE TRAVELS FROM GEO TO LLO -- LOADED                    (IFN = 8)
C SHUTTLE TRAVELS FROM GEO TO L4  -- LOADED                    (IFN = 9)
C SHUTTLE TRAVELS FROM GEO TO L4  -- UNLOADED                  (IFN = 10)
C SHUTTLE TRAVELS FROM GEO TO L2  -- UNLOADED                  (IFN = 11)
C
C LOW LUNAR ORBIT (LLO)
C
C SHUTTLE TRAVELS FROM LLO TO L5  -- LOADED                    (IFN = 12)
C SHUTTLE TRAVELS FROM LLO TO L4  -- LOADED                    (IFN = 13)
C SHUTTLE TRAVELS FROM LLO TO LEO -- LOADED                    (IFN = 14)
C SHUTTLE TRAVELS FROM LLO TO GEO -- LOADED                    (IFN = 15)
C SHUTTLE TRAVELS FROM LLO TO L2  -- LOADED                    (IFN = 16)
C SHUTTLE TRAVELS FROM LLO TO L2  -- UNLOADED                  (IFN = 17)
C
C UNSTABLE LAGRANGIAN POINT TWO (L2)
C
C SHUTTLE TRAVELS FROM L2  TO L5  -- LOADED (LUNAR ORE)        (IFN = 18)
C SHUTTLE TRAVELS FROM L2  TO LLO -- LOADED                    (IFN = 19)
C
C STABLE LAGRANGIAN POINT FOUR (L4)
C
C SHUTTLE TRAVELS FROM L4  TO LLO -- LOADED                    (IFN = 20)
C SHUTTLE TRAVELS FROM L4  TO L5  -- LOADED                    (IFN = 21)
C SHUTTLE TRAVELS FROM L4  TO LEO -- LOADED                    (IFN = 22)
C SHUTTLE TRAVELS FROM L4  TO GEO -- LOADED                    (IFN = 23)
C SHUTTLE TRAVELS FROM L4  TO L2  -- UNLOADED                  (IFN = 24)
C SHUTTLE TRAVELS FROM L4  TO GEO -- LOADED (SSPS PARTS)       (IFN = 25)
C
C STABLE LAGRANGIAN POINT FOUR (L5)
C
C SHUTTLE TRAVELS FROM L5  TO L4  -- LOADED                    (IFN = 26)
C SHUTTLE TRAVELS FROM L5  TO LLO -- LOADED                    (IFN = 27)
C SHUTTLE TRAVELS FROM L5  TO LEO -- LOADED                    (IFN = 28)
C SHUTTLE TRAVELS FROM L5  TO GEO -- LOADED                    (IFN = 29)
C SHUTTLE TRAVELS FROM L5  TO L2  -- UNLOADED                  (IFN = 30)
C SHUTTLE TRAVELS FROM L5  TO L4  -- LOADED (RAW MATERIALS)    (IFN = 31)
C SHUTTLE NEEDS MAJOR REPAIRS                                  (IFN = 32)
C SHUTTLE DAMAGED AND BEYOND REPAIRS, RETIRE SHIP              (IFN = 33)
C SHUTTLE IS PAST ITS NORMAL LIFETIME, RETIRE SHIP             (IFN = 34)
C
    1 CALL GETAT(ATT)
      I = IFIX(ATT(1))
      SHUTTLE(I,IFN) = SHUTTLE(I,IFN) + 1
      J = IFN + 40
      ATT(4) = 0.0
      IF (IFN.LE.31) ATT(4) = UN(J)
      CALL PUTAT(ATT)
      UF = 0.0
      RETURN
C
C
C STORE THE DATE A SHUTTLE IS TAKEN OUT OF SERVICE             (IFN = 35)
C
```

```
    2 CALL GETAT(ATT)
      I = IFIX(ATT(1))
      SHIP(I,2) = TNOW
      AGE = (SHIP(I,2) - SHIP(I,1)) / YEAR
      ATT(10) = 0.0
      IF (AGE.GE.LIFE) ATT(10) = 1.0
      CALL PUTAT(ATT)
      UF = 0.0
      RETURN
C
C
C INCREMENT THE NUMBER OF NEW SSPS'S AT GEO                         (IFN = 36)
C
    3 SSPS = SSPS + 1
      UF = 0.0
      RETURN
C
C
C INCREMENT THE NUMBER OF NEW COLONIES AT L4                        (IFN = 37)
C
    4 L4COLON = L4COLON + 1
      UF = 0.0
      RETURN
C
C
C INCREMENT THE NUMBER OF NEW COLONIES AT L5                        (IFN = 38)
C
    5 L5COLON = L5COLON + 1
      UF = 0.0
      RETURN
C
C
C INCREMENT THE NUMBER OF ASTEROIDS THAT ARRIVE AT L5               (IFN = 39)
C
    6 ASTER = ASTER + 1
      UF = WEIGHT
      RETURN
C
C
C GET PROBABILITIES (IFN = 40 TO 58)
C
C LEO
C
C WILL SHUTTLE LEAVING LEO BE LOADED OF UNLOADED?                   (IFN = 40)
C DESTINATION OF A SHUTTLE LEAVING LEO (LOADED)?                    (IFN = 41)
C
C GEO
C
C WILL SHUTTLE LEAVING GEO BE LOADED OR UNLOADED?                   (IFN = 42)
C DESTINATION OF A SHUTTLE LEAVING GEO (UNLOADED)?                  (IFN = 43)
C DESTINATION OF A SHUTTLE LEAVING GEO (LOADED)?                    (IFN = 44)
C
C LLO
C
```

```
C WILL SHUTTLE GO TO L2?                                      (IFN = 45)
C WILL SHUTTLE LEAVING LLO BE LOADED OR UNLOADED?             (IFN = 46)
C DESTINATION OF A SHUTTLE LEAVING LLO (LOADED)?              (IFN = 47)
C
C L2
C
C WHAT TYPE OF CARGO WILL LEAVE L2?                           (IFN = 48)
C
C L4
C
C WHERE WILL THE RAW MATERIALS FROM L5 BE USED AT L4?         (IFN = 49)
C WILL SHUTTLE LEAVING L4 BE LOADED OR UNLOADED?              (IFN = 50)
C WHAT TYPE OF CARGO WILL LEAVE L4?                           (IFN = 51)
C DESTINATION OF A SHUTTLE LEAVING L4 (LOADED)?               (IFN = 52)
C
C L5
C
C WHEN SHUTTLE ARRIVES AT L5, DOES IT REQUIRE MAJOR REPAIRS? (IFN = 53)
C CAN THE SHUTTLE BE REPAIRED?                                (IFN = 54)
C WILL SHUTTLE LEAVING L5 BE LOADED OR UNLOADED?              (IFN = 55)
C WHERE/HOW WILL THE RAW MATERIAL BE USED?                    (IFN = 56)
C WHAT TYPE OF CARGO WILL LEAVE L5?                           (IFN = 57)
C DESTINATION OF A SHUTTLE LEAVING L5 (LOADED)?               (IFN = 58)
C
    7 CALL GETAT(ATT)
      J = IFN - 39
      ATT(5) = PROB(J,1)
      ATT(6) = PROB(J,2)
      ATT(7) = PROB(J,3)
      ATT(8) = PROB(J,4)
      CALL PUTAT(ATT)
      UF = 0.0
      RETURN
C
C
C INCREMENT THE NUMBER OF CHUNKS, THE SIZE OF A SHIP'S CARGO,
C OF ASTEROIDAL ORE THAT HAVE BEEN MINED                      (IFN = 59)
C
    8 GETAT(ATT)
      UF = ATT(2) 1.0
      RETURN
C
C
      END
```

```
      SUBROUTINE US(ISN,DTIM)
C
C
C US                    THE Q-GERT USER SUBROUTINE (US) IS ALMOST COMPLETELY
C                       INTERCHANGEABLE WITH UF.  THE US SUBROUTINE IN THIS
C                       PROGRAM IS USED MAINLY TO DETERMINE IF A NEW SHUTTLE
C                       IS NEEDED IN THE SIMULATION.  THE "OPTIMUM NUMBER OF
C                       SHUTTLES" IN THIS SIMULATION IS DEFINED AS THE NUMBER
C                       OF SHUTTLES NEEDED TO ALLOW A CARGO OF RAW MATERIALS
C                       FROM L5 TO L4 TO ALWAYS HAVE A SHUTTLE AVAILABLE.
C
C ISN                   THE USER SUBROUTINE NUMBER (ISN) TELLS WHAT PART OF
C                       SUBROUTINE THAT WILL BE PROCESSED.
C
C DTIM                  VARIABLE WHICH STORES THE VALUE/RESULT OF THE US
C                       SUBROUTINE
C
C
C
      COMMON /QVAR/ NDE,NFTBU(500),NREL(500),NRELP(500),NREL2(500),
     1              NRUN,NRUNS,NTC(500),PARAM(100,4),TBEG,TNOW
C
      REAL AGE,ATT(10),AVERAGE,LIFE,PROB(19,4),SHIP(1500,2),WEIGHT,
     1     YEAR,YEARS
C
      INTEGER ACTIVE,ASTER,L4COLON,L5COLON,MAXSHIP,NODE,QNODE,SHIPNO,
     1        SHUTTLE(1500,35),SIZE,SSPS,TOTAL(14)
C
      COMMON /INFO/ ACTIVE,AGE,ASTER,ATT,AVERAGE,LIFE,L4COLON,L5COLON,
     1              MAXSHIP,NODE,PROB,QNODE,SHIP,SHIPNO,SHUTTLE,SIZE,
     2              SSPS,TOTAL,WEIGHT,YEAR,YEARS
C
C
C
C GO TO THE PROPER ROUTINE BASED ON THE ISN
      GO TO (1,2),ISN
C
C
C IS A NEW SHUTTLE NEEDED TO CARRY A RAW MATERIALS CARGO FROM L5 TO L4?
C
    1 IF (NREL(QNODE).GT.0) GO TO 20
C
C A NEW SHUTTLE IS NEEDED
C
      SHIPNO = SHIPNO + 1
      ATT(1) = FLOAT(SHIPNO)
      DO 10 I = 2,10
      ATT(I) = 0.0
   10 CONTINUE
C
C PUT A NEW SHUTTLE INTO THE SYSTEM
C
      CALL PTIN(NODE,0.0,TNOW,ATT)
C
```

```
C FLAG A SHUTTLE AS ACTIVE
C
      SHUTTLE(SHIPNO,ACTIVE) = SHUTTLE(SHIPNO,ACTIVE) + 1
C
C STORE THE DATE A SHUTTLE IS PUT INTO SERVICE
C
      SHIP(SHIPNO,1) = TNOW
C
   20 DTIM = 0.0
      RETURN
C
C
C A NEW SHUTTLE IS NEEDED AT THE BEGINING OF THE SIMULATION
C
    2 CALL GETAT(ATT)
      SHIPNO = SHIPNO + 1
      ATT(1) = FLOAT(SHIPNO)
      DO 30 I = 2,10
      ATT(I) = 0.0
   30 CONTINUE
      CALL PUTAT(ATT)
C
C FLAG A SHUTTLE AS ACTIVE
C
      SHUTTLE(SHIPNO,ACTIVE) = SHUTTLE(SHIPNO,ACTIVE) + 1
C
C STORE THE DATE A SHUTTLE IS PUT INTO SERVICE
C
      SHIP(SHIPNO,1) = TNOW
C
      DTIM = 0.0
      RETURN
C
C
      END
```

```
      SUBROUTINE UI
C
C
C
C UI                THE Q-GERT USER INPUT SUBROUTINE (UI) IS TO PROVIDE
C                   THE USER THE CAPABILITY TO INITIALIZE THE NETWORK
C                   FOR EACH RUN OF THE SIMULATION.  THE UI SUBROUTINE
C                   IN THIS PROGRAM INITIALIZES ALL CONSTANTS USED IN
C                   OTHER PARTS OF THE PROGRAM, ZEROES OUT THE SHUTTLE
C                   RELATED ARRAYS AND THE PRODUCTION VARIABLES
C                   (L4COLON, L5COLON, SSPS, AND ASTER), AND INITALIZES
C                   THE PROBABILITIES USED BY THE Q-GERT PROGRAM FOR
C                   BRANCHING.
C
C
C
      COMMON /QVAR/ NDE,NFTBU(500),NREL(500),NRELP(500),NREL2(500),
     1              NRUN,NRUNS,NTC(500),PARAM(100,4),TBEG,TNOW
C
      REAL AGE,ATT(10),AVERAGE,LIFE,PROB(19,4),SHIP(1500,2),WEIGHT,
     1    YEAR,YEARS
C
      INTEGER ACTIVE,ASTER,L4COLON,L5COLON,MAXSHIP,NODE,QNODE,SHIPNO,
     1       SHUTTLE(1500,35),SIZE,SSPS,TOTAL(14)
C
      COMMON /INFO/ ACTIVE,AGE,ASTER,ATT,AVERAGE,LIFE,L4COLON,L5COLON,
     1              MAXSHIP,NODE,PROB,QNODE,SHIP,SHIPNO,SHUTTLE,SIZE,
     2              SSPS,TOTAL,WEIGHT,YEAR,YEARS
C
C
C
C FOR ALL RUNS INITIALIZE THE FOLLOWING VARIABLES
C
C INITIALIZE THE CONSTANTS USED IN THE MODEL
C
      ACTIVE = 35
      LIFE = 10.0
      MAXSHIP = 1500
      NODE = 157
      QNODE = 160
      SHIPNO = 0
      SIZE = 1500
      WEIGHT = 350.0
      YEAR = 365.0
      YEARS = 50.0
C
C INITIALIZE THE SHUTTLE RELATED ARRAYS     (IFN = 1 TO 35 AND ISN = 1)
C
      DO 20 I = 1,MAXSHIP
      DO 10 J = 1,ACTIVE
      SHUTTLE  (I,J) = 0
   10 CONTINUE
      SHIP  (I,1` = 0.0
      SHIP  (I,2) = 0.0
```

```
   20 CONTINUE
C
C INITIALIZE THE NUMBER OF NEW SSPS'S AT GEO                        (IFN = 36)
C
      SSPS = 0
C
C INITIALIZE THE NUMBER OF NEW COLONIES AT L4                        (IFN = 37)
C
      L4COLON = 0
C
C INITIALIZE THE NUMBER OF NEW COLONIES AT L5                        (IFN = 38)
C
      L5COLON = 0
C
C INITIALIZE THE NUMBER OF ASTEROIDS THAT ARRIVE AT L5               (IFN = 39)
C
      ASTER = 0
C
C
C IF THIS IS THE FIRST RUN, THEN INITIALIZE THE REMAINING VARIABLES
C
      IF (NRUN.NE.1) RETURN
C
C
C
C
C INITIALIZE THE PROBABILITIES USED IN THE MODEL         (IFN = 40 TO 58)
C
C
C
C LOW EARTH ORBIT (LEO)
C
C
C WILL SHUTTLE LEAVING LEO BE LOADED OF UNLOADED?                   (IFN = 40)
C
C LOADED
      PROB(1,1) = 0.80
C UNLOADED TO L2
      PROB(1,2) = 0.20
C NOT USED
      PROB(1,3) = 0.00
      PROB(1,4) = 0.00
C
C DESTINATION OF A SHUTTLE LEAVING LEO (LOADED)?                    (IFN = 41)
C
C GEO
      PROB(2,1) = 0.10
C L5
      PROB(2,2) = 0.30
C L4
      PROB(2,3) = 0.30
C LLO
      PROB(2,4) = 0.30
C
```

```
C
C
C GEOSTATIONARY EARTH ORBIT (GEO)
C
C
C WILL SHUTTLE LEAVING GEO BE LOADED OR UNLOADED?            (IFN = 42)
C
C LOADED
      PROB(3,1) = 0.20
C UNLOADED
      PROB(3,2) = 0.80
C NOT USED
      PROB(3,3) = 0.00
      PROB(3,4) = 0.00
C
C DESTINATION OF A SHUTTLE LEAVING GEO (UNLOADED)?           (IFN = 43)
C
C L4
      PROB(4,1) = 0.20
C L2
      PROB(4,2) = 0.80
C NOT USED
      PROB(4,3) = 0.00
      PROB(4,4) = 0.00
C
C DESTINATION OF A SHUTTLE LEAVING GEO (LOADED)?             (IFN = 44)
C
C LEO
      PROB(5,1) = 0.25
C L5
      PROB(5,2) = 0.25
C LLO
      PROB(5,3) = 0.25
C L4
      PROB(5,4) = 0.25
C
C
C
C LOW LUNAR ORBIT (LLO)
C
C
C WILL SHUTTLE GO TO L2?                                     (IFN = 45)
C
C NO, GO TO ANOTHER DESTINATION
      PROB(6,1) = 0.80
C YES, GO TO L2
      PROB(6,2) = 0.20
C NOT USED
      PROB(6,3) = 0.00
      PROB(6,4) = 0.00
C
C WILL SHUTTLE LEAVING LLO BE LOADED OR UNLOADED?            (IFN = 46)
C
C LOADED TO L2
```

```
      PROB(7,1) = 0.80
C UNLOADED TO L2
      PROB(7,2) = 0.20
C NOT USED
      PROB(7,3) = 0.00
      PROB(7,4) = 0.00
C
C DESTINATION OF A SHUTTLE LEAVING LLO (LOADED)?          (IFN = 47)
C
C L5
      PROB(8,1) = 0.30
C L4
      PROB(8,2) = 0.30
C LEO
      PROB(8,3) = 0.30
C GEO
      PROB(8,4) = 0.10
C
C
C
C UNSTABLE LAGRANGIAN POINT TWO (L2)
C
C
C WHAT TYPE OF CARGO WILL LEAVE L2?                       (IFN = 48)
C
C LUNAR ORE FOR L5
      PROB(9,1) = 0.95
C MISC CARGO
      PROB(9,2) = 0.05
C NOT USED
      PROB(9,3) = 0.00
      PROB(9,4) = 0.00
C
C
C
C STABLE LAGRANGIAN POINT FOUR (L4)
C
C
C WHERE WILL THE RAW MATERIALS FROM L5 BE USED AT L4?     (IFN = 49)
C
C BUILDING SSPS PARTS
      PROB(10,1) = 0.20
C BUILDING NEW COLONIES
      PROB(10,2) = 0.80
C NOT USED
      PROB(10,3) = 0.00
      PROB(10,4) = 0.00
C
C WILL SHUTTLE LEAVING L4 BE LOADED OR UNLOADED?          (IFN = 50)
C
C UNLOADED TO L2
      PROB(11,1) = 0.20
C LOADED
      PROB(11,2) = 0.80
```

```
C NOT USED
      PROB(11,3) = 0.00
      PROB(11,4) = 0.00
C
C WHAT TYPE OF CARGO WILL LEAVE L4?                        (IFN = 51)
C
C MISC CARGO
      PROB(12,1) = 0.80
C SSPS PARTS FOR GEO
      PROB(12,2) = 0.20
C NOT USED
      PROB(12,3) = 0.00
      PROB(12,4) = 0.00
C
C DESTINATION OF A SHUTTLE LEAVING L4 (LOADED)?            (IFN = 52)
C
C LLO
      PROB(13,1) = 0.30
C L5
      PROB(13,2) = 0.30
C LEO
      PROB(13,3) = 0.30
C GEO
      PROB(13,4) = 0.10
C
C
C
C STABLE LAGRANGIAN POINT FIVE (L5)
C
C
C WHEN SHUTTLE ARRIVES AT L5, DOES IT REQUIRE MAJOR REPAIRS? (IFN = 53)
C
C NO, NEEDS ONLY NORMAL REPAIRS
      PROB(14,1) = 0.95
C YES, SHUTTLE NEEDS MAJOR REPAIRS
      PROB(14,2) = 0.05
C NOT USED
      PROB(14,3) = 0.00
      PROB(14,4) = 0.00
C
C CAN THE SHUTTLE BE REPAIRED?                             (IFN = 54)
C
C YES, REPAIR THE SHUTTLE
      PROB(15,1) = 0.95
C NO, RETIRE THE SHUTTLE
      PROB(15,2) = 0.05
C NOT USED
      PROB(15,3) = 0.00
      PROB(15,4) = 0.00
C
C WILL SHUTTLE LEAVING L5 BE LOADED OR UNLOADED?           (IFN = 55)
C
C UNLOADED TO L2
      PROB(16,1) = 0.30
```

```
C LOADED
      PROB(16,2) = 0.70
C NOT USED
      PROB(16,3) = 0.00
      PROB(16,4) = 0.00
C
C WHERE/HOW WILL THE RAW MATERIAL BE USED?                        (IFN = 56)
C
C WASTE OR SLAG
      PROB(17,1) = 0.20
C L5 (COLONIES)
      PROB(17,2) = 0.35
C L4 (COLONIES AND SSPS'S)
      PROB(17,3) = 0.45
C NOT USED
      PROB(17,4) = 0.00
C
C WHAT TYPE OF CARGO WILL LEAVE L5?                               (IFN = 57)
C
C RAW MATERIALS FOR L4
      PROB(18,1) = 0.80
C MISC CARGO
      PROB(18,2) = 0.20
C NOT USED
      PROB(18,3) = 0.00
      PROB(18,4) = 0.00
C
C DESTINATION OF A SHUTTLE LEAVING L5 (LOADED)?                   (IFN = 58)
C
C L4
      PROB(19,1) = 0.30
C LLO
      PROB(19,2) = 0.30
C LEO
      PROB(19,3) = 0.30
C GEO
      PROB(19,4) = 0.10
C
C
      RETURN
C
C
      END
```

```
      SUBROUTINE UO
C
C
C
C UO                 THE Q-GERT USER OUTPUT SUBROUTINE (UO) IS TO PROVIDE
C                    THE USER THE CAPABILITY TO OUTPUT USER STATISTICS
C                    AND ANY OTHER INFORMATION THAT THE USER DEEMS NECES-
C                    SARY.  THE UO SUBROUTINE IN THIS PROGRAM OUTPUTS THE
C                    SHUTTLE RELATED ARRAYS AND THE PRODUCTION VARIABLES.
C
C
C
      COMMON /QVAR/ NDE,NFTBU(500),NREL(500),NRELP(500),NREL2(500),
     1              NRUN,NRUNS,NTC(500),PARAM(100,4),TBEG,TNOW
C
      REAL AGE,ATT(10),AVERAGE,LIFE,PROB(19,4),SHIP(1500,2),WEIGHT,
     1     YEAR,YEARS
C
      INTEGER ACTIVE,ASTER,L4COLON,L5COLON,MAXSHIP,NODE,QNODE,SHIPNO,
     1        SHUTTLE(1500,35),SIZE,SSPS,TOTAL(14)
C
      COMMON /INFO/ ACTIVE,AGE,ASTER,ATT,AVERAGE,LIFE,L4COLON,L5COLON,
     1              MAXSHIP,NODE,PROB,QNODE,SHIP,SHIPNO,SHUTTLE,SIZE,
     2              SSPS,TOTAL,WEIGHT,YEAR,YEARS
C
C
C
C SETUP THE FORMATS USED TO PRESENT USER GENERATED STATISTICS
C
C
 1000 FORMAT (54H1ACTIVITY MATRIX FOR SHUTTLES AT LOW EARTH ORBIT (LEO))
 1100 FORMAT (54H -----------------------------------------------------,
     1        / / )
 1200 FORMAT (45H SHUTTLE NUMBER   LEO/GEO    LEO/L5    LEO/L4,
     1        40H   LEO/LLO    LEO/L2(UNLOADED)     TOTAL)
 1300 FORMAT (45H --------------   -------    ------    ------,
     1        40H   -------    ----------------     -----)
 1400 FORMAT (6X,I3,6X,I10,I10,I10,I10,I20,I10)
 1500 FORMAT (7H TOTALS,8X,I10,I10,I10,I10,I20,I10)
C
C
 2000 FORMAT (53H1ACTIVITY MATRIX FOR SHUTTLES AT GEOSTATIONARY EARTH ,
     1        11HORBIT (GEO))
 2100 FORMAT (53H ----------------------------------------------------,
     1        11H---------- / / )
 2200 FORMAT (45H SHUTTLE NUMBER   GEO/LEO    GEO/L5   GEO/LLO,
     1        45H   GEO/L4    GEO/L4(UNLOADED)    GEO/L2(UNLO,
     2        15HADED)     TOTAL)
 2300 FORMAT (45H --------------   -------    ------   -------,
     1        45H    ------    ----------------    -----------,
     2        15H-----      -----)
 2400 FORMAT (6X,I3,6X,I10,I10,I10,I10,I20,I20,I10)
 2500 FORMAT (7H TOTALS,8X,I10,I10,I10,I10,I20,I20,I10)
C
```

```
C
 3000 FORMAT (54H1ACTIVITY MATRIX FOR SHUTTLES AT LOW LUNAR ORBIT (LLO))
 3100 FORMAT (54H ----------------------------------------------------,
     1        / / )
 3200 FORMAT (45H SHUTTLE NUMBER    LLO/L5    LLO/L4   LLO/LEO,
     1         45H   LLO/GEO      LLO/L2(LOADED)    LLO/L2(UNLO,
     2         15HADED)     TOTAL)
 3300 FORMAT (45H --------------    ------    ------   -------,
     1         45H   -------      --------------    -----------,
     2         15H-----       -----)
 3400 FORMAT (6X,I3,6X,I10,I10,I10,I10,I20,I20,I10)
 3500 FORMAT (7H TOTALS,8X,I10,I10,I10,I10,I20,I20,I10)
C
C
 4000 FORMAT (46H1ACTIVITY MATRIX FOR SHUTTLES AT THE UNSTABLE ,
     1        25HLAGRANGIAN POINT TWO (L2))
 4100 FORMAT (46H --------------------------------------------,
     1        25H----------------------- / / )
 4200 FORMAT (45H SHUTTLE NUMBER    L2/L5(LUNAR ORE)       L2/L,
     1        20HLO(LOADED)     TOTAL)
 4300 FORMAT (45H --------------    ----------------       ----,
     1        20H----------     -----)
 4400 FORMAT (6X,I3,6X,I20,I20,I10)
 4500 FORMAT (7H TOTALS,8X,I20,I20,I10)
C
C
 5000 FORMAT (44H1ACTIVITY MATRIX FOR SHUTTLES AT THE STABLE ,
     1        26HLAGRANGIAN POINT FOUR (L4))
 5100 FORMAT (44H ------------------------------------------,
     1        26H------------------------- / / )
 5200 FORMAT (45H SHUTTLE NUMBER    L4/LLO     L4/L5    L4/LEO,
     1         45H    L4/GEO     L4/L2(UNLOADED)         L4/GEO(,
     2         15HSSPS)     TOTAL)
 5300 FORMAT (45H --------------    ------     -----    ------,
     1         45H    ------     ---------------         -------,
     2         15H-----       -----)
 5400 FORMAT (6X,I3,6X,I10,I10,I10,I10,I20,I20,I10)
 5500 FORMAT (7H TOTALS,8X,I10,I10,I10,I10,I20,I20,I10)
C
C
 6000 FORMAT (44H1ACTIVITY MATRIX FOR SHUTTLES AT THE STABLE ,
     1        26HLAGRANGIAN POINT FIVE (L5))
 6100 FORMAT (44H ------------------------------------------,
     1        26H------------------------- / / )
 6200 FORMAT (45H SHUTTLE NUMBER     L5/L4    L5/LLO    L5/LEO,
     1         45H    L5/GEO     L5/L2(UNLOADED)          L5/L4,
     2         15H(RAW)     TOTAL)
 6300 FORMAT (45H --------------     -----    ------    ------,
     1         45H    ------     ---------------          -----,
     2         15H-----       -----)
 6400 FORMAT (6X,I3,6X,I10,I10,I10,I10,I20,I20,I10)
 6500 FORMAT (7H TOTALS,8X,I10,I10,I10,I10,I20,I20,I10)
C
C
```

```
 7000 FORMAT (50H1ACTIVITY MATRIX FOR SHUTTLES AT ALL NODES OF THE ,
     1           7HNETWORK)
 7100 FORMAT (50H --------------------------------------------------,
     1           7H------- / / )
 7200 FORMAT (45H SHUTTLE NUMBER        LEO        GEO        LLO,
     1          40H           L2          L4          L5     TOTAL)
 7300 FORMAT (45H --------------        ---        ---        ---,
     1          40H           --          --          --     -----)
 7400 FORMAT (6X,I3,6X,I10,I10,I10,I10,I10,I10,I10)
 7500 FORMAT (7H TOTALS,8X,I10,I10,I10,I10,I10,I10,I10)
C
C
 8000 FORMAT (49H1VITAL STATISTICS ON ALL THE INTER-ORBIT SHUTTLES)
 8100 FORMAT (49H ------------------------------------------------ / / )
 8200 FORMAT (45H SHUTTLE NUMBER     DATE BUILT   DATE RETIRED,
     1          45H              AGE    TOTAL TRIPS       AVE TRIPS,
     2          30H   REPAIRS   DAMAGED   OLD AGE)
 8300 FORMAT (45H --------------     ----------   ------------,
     1          45H              ---    -----------      ---------,
     2          30H   -------   -------   -------)
 8400 FORMAT (6X,I3,6X,F15.5,F15.5,F15.5,I15,F15.5,I10,I10,I10)
 8500 FORMAT (7H TOTALS,8X,50X,I10,15X,I10,I10,I10)
C
C
 9000 FORMAT (12H1DURING THE , F8.2, 19H YEARS INVESTIGATED,
     1           38H IN THIS STUDY THE FOLLOWING HAPPENED: / / / /
     2           45H STARTING WITH ONE COLONY AT L4 AND ONE AT L5,
     3           48H AND NO SSPS'S AT GEO, THE FOLLOWING WERE BUILT: /
     4           I10, 15H COLONIES AT L4 /
     5           I10, 15H COLONIES AT L5 /
     6           I10, 14H SSPS'S AT GEO / / / /
     7           27H TOTAL NUMBER OF SHUTTLES ( , I5,
     8           17H METRIC TONS) IS ,I10 / / / /
     9           44H TOTAL NUMBER OF TRIPS THAT WERE MADE BY ALL,
     A           13H SHUTTLES IS ,I10 / / / /
     B           52H TOTAL NUMBER OF MAJOR REPAIRS THAT WERE DONE ON ALL,
     C           13H SHUTTLES IS ,I10 / / / /
     D           50H TOTAL NUMBER OF SHUTTLES THAT WERE DAMAGED BEYOND,
     E           11H REPAIR IS ,I10 / / / /
     F           51H TOTAL NUMBER OF SHUTTLES THAT WERE RETIRED BECAUSE,
     G           11H OF AGE IS ,I10)
C
 9100 FORMAT (1H  / / / 37H AVERAGE NUMBER OF TRIPS PER YEAR IS ,
     1           F15.5, / / / /
     2           51H THE TOTAL NUMBER OF ASTEROIDS RETREIVED FOR MINING,
     3            4H IS , I10 / / / /
     4           49H THE TOTAL MASS OF ASTEROIDAL ORE MINED AT L5 IS ,
     5           I20, 12H METRIC TONS / / / /
     6           46H THE TOTAL NUMBER OF LUNAR ORE TRIPS TO L5 IS ,
     7           I10 / / / /
     8           43H THE TOTAL MASS OF LUNAR ORE SENT TO L5 IS , I20,
     9           12H METRIC TONS)
C
C
```

```
C PRINT OUT WHAT THE SHUTTLE HAS BEEN DOING AT EACH NODE OF THE SYSTEM
C
C
C LOW EARTH ORBIT (LEO)
C
      PRINT 1000
      PRINT 1100
      PRINT 1200
      PRINT 1300
C
      DO 110 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 110
      TOTAL(1) = 0
C
      DO 100 J = 1,5
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,J)
  100 CONTINUE
C
      PRINT 1400,I,(SHUTTLE(I,J),J=1,5),TOTAL(1)
  110 CONTINUE
C
      DO 120 K = 1,7
      TOTAL(K) = 0
  120 CONTINUE
C
      DO 130 J = 1,5
      DO 130 I = 1,MAXSHIP
      K = J
      TOTAL(K) = TOTAL(K) + SHUTTLE(I,J)
  130 CONTINUE
C
      TOTAL(6) = TOTAL(1) + TOTAL(2) + TOTAL(3) +
     1           TOTAL(4) + TOTAL(5)
C
      PRINT 1300
      PRINT 1500,(TOTAL(K),K=1,6)
C
C
C GEOSTATIONARY EARTH ORBIT (GEO)
C
      PRINT 2000
      PRINT 2100
      PRINT 2200
      PRINT 2300
C
      DO 150 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 150
      TOTAL(1) = 0
C
      DO 140 J = 6,11
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,J)
  140 CONTINUE
C
      PRINT 2400,I,(SHUTTLE(I,J),J=6,11),TOTAL(1)
```

```
  150 CONTINUE
C
      DO 160 K = 1,7
      TOTAL(K) = 0
  160 CONTINUE
C
      DO 170 J = 6,11
      DO 170 I = 1,MAXSHIP
      K = J - 5
      TOTAL(K) = TOTAL(K) + SHUTTLE(I,J)
  170 CONTINUE
C
      TOTAL(7) = TOTAL(1) + TOTAL(2) + TOTAL(3) +
     1           TOTAL(4) + TOTAL(5) + TOTAL(6)
C
      PRINT 2300
      PRINT 2500,(TOTAL(K),K=1,7)
C
C
C LOW LUNAR ORBIT (LLO)
C
      PRINT 3000
      PRINT 3100
      PRINT 3200
      PRINT 3300
C
      DO 190 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 190
      TOTAL(1) = 0
C
      DO 180 J = 12,17
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,J)
  180 CONTINUE
C
      PRINT 3400,I,(SHUTTLE(I,J),J=12,17),TOTAL(1)
  190 CONTINUE
C
      DO 200 K = 1,7
      TOTAL(K) = 0
  200 CONTINUE
C
      DO 210 J = 12,17
      DO 210 I = 1,MAXSHIP
      K = J - 11
      TOTAL(K) = TOTAL(K) + SHUTTLE(I,J)
  210 CONTINUE
C
      TOTAL(7) = TOTAL(1) + TOTAL(2) + TOTAL(3) +
     1           TOTAL(4) + TOTAL(5) + TOTAL(6)
C
      PRINT 3300
      PRINT 3500,(TOTAL(K),K=1,7)
C
C
```

```
C UNSTABLE LAGRANGIAN POINT TWO (L2)
C
      PRINT 4000
      PRINT 4100
      PRINT 4200
      PRINT 4300
C
      DO 230 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 230
      TOTAL(1) = 0
C
      DO 220 J = 18,19
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,J)
  220 CONTINUE
C
      PRINT 4400,I,(SHUTTLE(I,J),J=18,19),TOTAL(1)
  230 CONTINUE
C
      DO 240 K = 1,7
      TOTAL(K) = 0
  240 CONTINUE
C
      DO 250 J = 18,19
      DO 250 I = 1,MAXSHIP
      K = J - 17
      TOTAL(K) = TOTAL(K) + SHUTTLE(I,J)
  250 CONTINUE
C
      TOTAL(3) = TOTAL(1) + TOTAL(2)
C
      PRINT 4300
      PRINT 4500,(TOTAL(K),K=1,3)
C
C
C STABLE LAGRANGIAN POINT FOUR (L4)
C
      PRINT 5000
      PRINT 5100
      PRINT 5200
      PRINT 5300
C
      DO 270 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 270
      TOTAL(1) = 0
C
      DO 260 J = 20,25
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,J)
  260 CONTINUE
C
      PRINT 5400,I,(SHUTTLE(I,J),J=20,25),TOTAL(1)
  270 CONTINUE
C
      DO 280 K = 1,7
      TOTAL(K) = 0
```

```
  280 CONTINUE
C
      DO 290 J = 20,25
      DO 290 I = 1,MAXSHIP
      K = J - 19
      TOTAL(K) = TOTAL(K) + SHUTTLE(I,J)
  290 CONTINUE
C
      TOTAL(7) = TOTAL(1) + TOTAL(2) + TOTAL(3) +
     1           TOTAL(4) + TOTAL(5) + TOTAL(6)
C
      PRINT 5300
      PRINT 5500,(TOTAL(K),K=1,7)
C
C
C STABLE LAGRANGIAN POINT FIVE (L5)
C
      PRINT 6000
      PRINT 6100
      PRINT 6200
      PRINT 6300
C
      DO 310 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 310
      TOTAL(1) = 0
C
      DO 300 J = 26,31
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,J)
  300 CONTINUE
C
      PRINT 6400,I,(SHUTTLE(I,J),J=26,31),TOTAL(1)
  310 CONTINUE
C
      DO 320 K = 1,7
      TOTAL(K) = 0
  320 CONTINUE
C
      DO 330 J = 26,31
      DO 330 I = 1,MAXSHIP
      K = J - 25
      TOTAL(K) = TOTAL(K) + SHUTTLE(I,J)
  330 CONTINUE
C
      TOTAL(7) = TOTAL(1) + TOTAL(2) + TOTAL(3) +
     1           TOTAL(4) + TOTAL(5) + TOTAL(6)
C
      PRINT 6300
      PRINT 6500,(TOTAL(K),K=1,7)
C
C
C
C PRINT OUT THE TOTAL TIMES A SHUTTLE ARRIVES AT A NODE IN THE SYSTEM
C
      PRINT 7000
```

```
      PRINT 7100
      PRINT 7200
      PRINT 7300
C
      DO 340 K = 1,14
      TOTAL(K) = 0
  340 CONTINUE
C
      DO 360 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 360
C
C LEO
C
      TOTAL(1) = SHUTTLE(I,6)  + SHUTTLE(I,14) + SHUTTLE(I,22) +
     1           SHUTTLE(I,28)
      TOTAL(8) = TOTAL(8) + TOTAL(1)
C
C GEO
C
      TOTAL(2) = SHUTTLE(I,1)  + SHUTTLE(I,15) + SHUTTLE(I,23) +
     1           SHUTTLE(I,25) + SHUTTLE(I,29)
      TOTAL(9) = TOTAL(9) + TOTAL(2)
C
C LLO
C
      TOTAL(3) = SHUTTLE(I,4)  + SHUTTLE(I,8)  + SHUTTLE(I,19) +
     1           SHUTTLE(I,20) + SHUTTLE(I,27)
      TOTAL(10) = TOTAL(10) + TOTAL(3)
C
C L2
C
      TOTAL(4) = SHUTTLE(I,5)  + SHUTTLE(I,11) + SHUTTLE(I,16)  +
     1           SHUTTLE(I,17) + SHUTTLE(I,24) + SHUTTLE(I,30)
      TOTAL(11) = TOTAL(11) + TOTAL(4)
C
C L4
C
      TOTAL(5) = SHUTTLE(I,3)  + SHUTTLE(I,9)  + SHUTTLE(I,10) +
     1           SHUTTLE(I,13) + SHUTTLE(I,26) + SHUTTLE(I,31)
      TOTAL(12) = TOTAL(12) + TOTAL(5)
C
C L5
C
      TOTAL(6) = SHUTTLE(I,2)  + SHUTTLE(I,7)  + SHUTTLE(I,12) +
     1           SHUTTLE(I,18) + SHUTTLE(I,21)
      TOTAL(13) = TOTAL(13) + TOTAL(6)
C
C TOTALS
C
      TOTAL(7) = TOTAL(1) + TOTAL(2) + TOTAL(3) +
     1           TOTAL(4) + TOTAL(5) + TOTAL(6)
      TOTAL(14) = TOTAL(14) + TOTAL(7)
C
      PRINT 7400,I,(TOTAL(K),K=1,7)
```

```
C
      DO 350 K = 1,7
      TOTAL(K) = 0
  350 CONTINUE
C
  360 CONTINUE
C
      PRINT 7300
      PRINT 7500,(TOTAL(K),K=8,14)
C
C
C PRINT OUT GENERAL INFORMATION ABOUT EACH SHUTTLE
C
      PRINT 8000
      PRINT 8100
      PRINT 8200
      PRINT 8300
C
      DO 370 K = 1,14
      TOTAL(K) = 0
  370 CONTINUE
C
      DO 390 I = 1,MAXSHIP
      IF (SHUTTLE(I,ACTIVE).NE.1) GO TO 390
C
      DO 380 J = 1,31
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,J)
  380 CONTINUE
C
      TOTAL(2) = TOTAL(2) + TOTAL(1)
      TOTAL(3) = TOTAL(3) + SHUTTLE(I,32)
      TOTAL(4) = TOTAL(4) + SHUTTLE(I,33)
      TOTAL(5) = TOTAL(5) + SHUTTLE(I,34)
C
C UPDATE THE TIME A SHIP "RETIRES" FOR SHUTTLES STILL ACTIVE
C AT THE END OF THE SIMULATION
C
      IF (SHUTTLE(I,33).EQ.0 .AND. SHUTTLE(I,34).EQ.0) SHIP(I,2) = TNOW
C
      AGE = (SHIP(I,2) - SHIP(I,1)) / YEAR
      AVERAGE = FLOAT(TOTAL(1)) / AGE
C
      PRINT 8400,I,SHIP(I,1),SHIP(I,2),AGE,TOTAL(1),AVERAGE,
     1            (SHUTTLE(I,J),J=32,34)
C
      TOTAL(1) = 0
  390 CONTINUE
C
      PRINT 8300
      PRINT 8500,(TOTAL(K),K=2,5)
C
C
C PRINT OUT THE INFORMATION ABOUT HOW MANY COLONIES AND SSPS'S
C WERE BUILT, TOTAL STATISTICS ABOUT SHUTTLES' ACTIVITIES AND
```

```
C ASTEROIDAL AND LUNAR ORE STATISTICS
C
      DO 400 K = 1,14
      TOTAL(K) = 0
  400 CONTINUE
C
      DO 420 I = 1,MAXSHIP
C
      DO 410 J = 1,31
      TOTAL(2) = TOTAL(2) + SHUTTLE(I,J)
  410 CONTINUE
C
      TOTAL(7) = TOTAL(7) + SHUTTLE(I,18)
      TOTAL(3) = TOTAL(3) + SHUTTLE(I,32)
      TOTAL(4) = TOTAL(4) + SHUTTLE(I,33)
      TOTAL(5) = TOTAL(5) + SHUTTLE(I,34)
      TOTAL(1) = TOTAL(1) + SHUTTLE(I,ACTIVE)
  420 CONTINUE
C
      AVERAGE = FLOAT(TOTAL(2)) / YEARS
      TOTAL(6) = ASTER * IFIX(WEIGHT) * SIZE
      TOTAL(8) = TOTAL(7) * SIZE
C
      PRINT 9000,YEARS,L4COLON,L5COLON,SSPS,SIZE,(TOTAL(K),K=1,5)
      PRINT 9100,AVERAGE,ASTER,(TOTAL(K),K=6,8)
C
C
      RETURN
C
C
      END
*EOR
```

```
GEN,WAGNER,SPACE-COLONY,12,15,1982,124,0,0,18250,1,E,0,11*
*
*
*
* THE FOLLOWING Q-GERT NETWORK IS A SIMULATION OF A TRANSPORTATION
* MODEL FOR A SPACE COLONIZATION AND MANUFACTURING SYSTEM (SCMS).
*
*
* ANY COMPUTER SYSTEM WHICH SUPPORTS FORTRAN IV AND Q-GERT SHOULD BE
* ABLE TO RUN THIS PROGRAM.  THE COMPUTER SYSTEM'S Q-GERT PROGRAM MUST
* BE ABLE TO UPDATE THE UF FUNCTION AND THE US, UI, AND UO SUBROUTINES.
* THE Q-GERT PROGRAM MUST ALSO BE ABLE TO HANDLE THE CHARACTERISTICS OF
* THIS Q-QERT NETWORK.
*
*
* THE Q-GERT NETWORK HAS THE FOLLOWING CHARACTERISTICS:
*
*      124     STATISTICS NODES
*       39     QUEUE NODES
*        6     SELECTOR NODES
*        1     SOURCE NODE
*     -----
*      170     TOTAL Q-GERT NODES
*
*      11 ATTRIBUTES PER TRANSACTION
*
*
*
```

```
*  LOW EARTH ORBIT (LEO)
*
* ON THE EARTH THERE ARE FACILITIES TO LAUNCH REUSABLE HEAVY LIFT
* VEHICLES (HLV) INTO LOW EARTH ORBIT WHERE THEY CAN DOCK TO A
* SPACE STATION.  IT IS ASSUMED THAT THE HLV HAS THE SAME CAPACITY
* AS AN INTER-ORBIT SHUTTLE (IOS).  IF THIS IS NOT TRUE, IT CAN BE
* ASSUMED THAT MULTIPLE (OR FRACTIONAL) LAUNCHES CAN EQUAL ONE
* PROPOSED HLV LAUNCH OR THE IOS LEAVES LEO ONLY PARTIALLY LOADED.
* THE SPACE TRANSPORTATON SYSTEM (STS) IS NOT SPECIFICALLY INCOR-
* PORATED INTO THIS MODEL BUT IT CAN BE ASSUMED THAT MULTIPLE STS
* LAUNCHES CAN EQUAL ONE HLV LAUNCH.
*
* IN LOW EARTH ORBIT THERE IS AN EARTH SPACE STATION (ESS) WHERE
* CARGO TO AND FROM THE EARTH IS TEMPORARILY STORED UNTIL THERE IS
* A SPACESHIP TO TRANSPORT THE CARGO TO ITS DESTINATION.  THE ESS
* ALSO HAS THE FACILITIES TO UNLOAD, SERVICE (MINIMUM), AND LOAD
* INTER-ORBIT SHUTTLES.
*
*
STA,1/ARR-LEO,1,1,D,B*                ARRIVE AT LEO LOADED WITH CARGO
ACT,1,2,CO,0*
QUE,2/UNLODOCK,0,,D,F*                LEO UNLOADING DOCK
VAS,2,2,CO,0*                         FLAG THE SHIP AS UNLOADED
ACT,2,3,UN,3,1/UNLO-LEO,1*            UNLOAD THE SHIP
STA,3/SHIP-UNLO,1,1,D,B*              SHIP IS UNLOADED
ACT,3,4,CO,0*
QUE,4/SERV-FAC,0,,D,F*                LEO SERVICE FACILITY
ACT,4,5,UN,4,2/SERV-LEO,1*            SERVICE THE SHIP
STA,5/LO-UNLO?,1,1,P,B*               WILL THE SHIP BE LOADED OR UNLOADED?
VAS,5,9,UF,40*                        (GET PROBABILITIES)
ACT,5,6,CO,0,,,5*                     (LOADED)
STA,6/LO-SHIP,1,1,D,B*                SHIP NEEDS TO BE LOADED
ACT,6,7,CO,0*
QUE,7/SHIPS-LEO,0,,D,F,,,,13*         SHIPS WAITING TO BE LOADED
VAS,7,2,CO,1*                         FLAG THE SHIP AS LOADED
ACT,5,8,UF,5,,,6*                     (UNLOADED)
STA,8/GO-TO-L2,1,1,D,B*               SEND THE SHIP TO L2 UNLOADED
ACT,8,64,AT,4*                        (L2)
STA,9/HLV-LAUN,1,1,D,B*               HLV LAUNCHES
ACT,9,9,UN,1*                         TIME BETWEEN HLV LAUNCHES
ACT,9,10,CO,0*
STA,10/PRE-CARGO,1,1,D,B*             COLLECT ALL THE HLV CARGOS
ACT,10,11,UN,2*                       PREPARE THE NEXT SHIP'S CARGO
STA,11/CARGO-PRE,1,1,D,B*             CARGO IS PREPARED
ACT,11,12,CO,0*
QUE,12/CARGO-LEO,0,,D,F,,,,13*        STORE THE SHIP'S CARGO
SEL,13/LOADDOCK,ASM,,B/1,,7,12*       LEO LOADING DOCK
ACT,13,14,UN,5,3/LOAD-LEO,1*          LOAD THE SHIP
STA,14/LEO-DES?,1,1,P,B*              WHAT IS THE SHIP'S DESTINATION?
VAS,14,9,UF,41*                       (GET PROBABILITIES)
ACT,14,15,UF,1,,,5*                   (GEO)
STA,15/LEO-GEO,1,1,D,B*               LEO TO GEO
ACT,15,19,AT,4*
ACT,14,16,UF,2,,,6*                   (L5)
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STA,16/LEO-L5,1,1,D,B*              LEO TO L5
ACT,16,117,AT,4*
ACT,14,17,UF,3,,,7*                 (L4)
STA,17/LEO-L4,1,1,D,B*              LEO TO L4
ACT,17,83,AT,4*
ACT,14,18,UF,4,,,8*                 (LLO)
STA,18/LEO-LLO,1,1,D,B*             LEO TO LLO
ACT,18,42,AT,4*
*
*
*
```

```
*  GEOSTATIONARY EARTH ORBIT (GEO)
*
* IN GEOSTATIONARY EARTH ORBIT THERE IS A SMALL SATELLITE CONSTRUCTION
* SHACK (SCS) TO PROVIDE FACILITIES TO A CREW OF WORKERS WHO PUT
* TOGETHER SATELLITE SOLAR POWER STATIONS (SSPS) FROM PARTS RECIEVED
* FROM L4.  THE SCS ALSO HAS THE FACILITIES TO UNLOAD, SERVICE
* (MINIMUM), AND LOAD INTER-ORBIT SHUTTLES.
*
*
STA,19/CARGO?,1,1,A,B*              ARRIVE AT GEO, WHAT TYPE OF CARGO?
ACT,19,20,CO,0,,,,A3.LE.0*          (MISC)
STA,20/MISC-GEO,1,1,D,B*            MISC CARGO
ACT,20,21,CO,0*
QUE,21/UNLODOC1,0,,D,F*             GEO UNLOADING DOCK ONE
VAS,21,2,CO,0*                      FLAG THE SHIP AS UNLOADED
ACT,21,22,UN,7,4/UNL1-GEO,1*        UNLOAD THE SHIP
STA,22/SHIP-UNLO,1,1,D,B*           SHIP IS UNLOADED OF MISC CARGO
ACT,22,29,CO,0*
ACT,19,23,CO,0,,,,A3.GT.0*          (SSPS)
STA,23/SSPS-GEO,1,1,D,B*            SSPS PARTS
ACT,23,24,CO,0*
QUE,24/UNLODOC2,0,,D,F*             GEO UNLOADING DOCK TWO
VAS,24,2,CO,0,3,CO,0*               FLAG THE SHIP AS UNLOADED
ACT,24,25,UN,8,5/UNL2-GEO,1*        UNLOAD THE SHIP OF SSPS PARTS
STA,25/SEPARATE,1,1,D,B*            SEPARATE CARGO FROM SHIP
ACT,25,26,CO,0*
QUE,26/SSPS-PARTS,0,,D,F*           SPSS PARTS STORAGE
ACT,26,27,UN,6,7/BUILDING,1*        PUT TOGETHER SSPS PARTS
STA,27/BUILD-SPSS,12,12,D,B*        BUILD A COMPLETE SSPS
ACT,27,28,UF,36*
STA,28/NEW-SSPS,1,1,D,B*            KEEP TRACK OF NEW SSPS'S
ACT,25,29,CO,0*
STA,29/SERV-SHIP,1,1,D,B*           SHIP NEEDS SERVICING
ACT,29,30,CO,0*
QUE,30/SERV-FAC,0,,D,F*             GEO SERVICE FACILITY
ACT,30,31,UN,9,6/SERV-GEO,1*        SERVICE THE SHIP
STA,31/LO-UNLO?,1,1,P,B*            WILL THE SHIP BE LOADED OR UNLOADED?
VAS,31,9,UF,42*                     (GET PROBABILITIES)
ACT,31,32,CO,0,,,5*                 (LOADED)
STA,32/LO-SHIP,1,1,D,B*             SHIP NEEDS TO BE LOADED
ACT,32,33,CO,0*
QUE,33/LOADDOCK,0,,D,F*             GEO LOADING DOCK
VAS,33,2,CO,1*                      FLAG THE SHIP AS LOADED
ACT,33,37,UN,10,8/LOAD-GEO,1*       LOAD THE SHIP
ACT,31,34,CO,0,,,6*                 (UNLOADED)
STA,34/GEO-D-U?,1,1,P,B*            WHAT IS THE SHIP'S DESTINATION
*                                   (UNLOADED)?
VAS,34,9,UF,43*                     (GET PROBABILITIES)
ACT,34,35,UF,10,,,5*                (L4)
STA,35/GO-TO-L4,1,1,D,B*            SEND SHIP TO L4 UNLOADED
ACT,35,83,AT,4*
ACT,34,36,UF,11,,,6*                (L2)
STA,36/GO-TO-L2,1,1,D,B*            SEND SHIP TO L2 UNLOADED
ACT,36,64,AT,4*
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STA,37/GEO-D-L?,1,1,P,B*          WHAT IS THE SHIP'S DESTINATION
*                                 (LOADED)?
VAS,37,9,UF,44*                   (GET PROBABILITIES)
ACT,37,38,UF,6,,,5*               (LEO)
STA,38/GEO-LEO,1,1,D,B*           GEO TO LEO
ACT,38,1,AT,4*
ACT,37,39,UF,7,,,6*               (L5)
STA,39/GEO-L5,1,1,D,B*            GEO TO L5
ACT,39,117,AT,4*
ACT,37,40,UF,8,,,7*               (LLO)
STA,40/GEO-LLO,1,1,D,B*           GEO TO LLO
ACT,40,42,AT,4*
ACT,37,41,UF,9,,,8*               (L4)
STA,41/GEO-L4,1,1,D,B*            GEO TO L4
ACT,41,83,AT,4*
*
*
*
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```
*  LOW LUNAR ORBIT (LLO)
*
* ON THE MOON THERE ARE FACILITIES TO LAUNCH REUSABLE LUNAR LAUNCH
* VEHICLES (LLV) INTO LOW LUNAR ORBIT WHERE THEY CAN DOCK TO A
* SPACE STATION.  IT IS ASSUMED THAT THE LLV HAS THE SAME CAPACITY
* AS AN INTER-ORBIT SHUTTLE.  IF THIS IS NOT TRUE, IT CAN BE ASSUMED
* THAT MULTIPLE (OR FRACTIONAL) LAUNCHES CAN EQUAL ONE PROPOSED LLV
* LAUNCH OR THE IOS LEAVES LLO ONLY PARTIALLY LOADED.
*
* IN LOW LUNAR ORBIT THERE IS A LUNAR SPACE STATION (LSS) WHERE
* CARGO TO AND FROM THE MOON IS TEMPORARILY STORED UNTIL THERE IS
* A SPACESHIP TO TRANSPORT THE CARGO TO ITS DESTINATION.  THE LSS
* ALSO HAS THE FACILITIES TO UNLOAD, SERVICE (MINIMUM), AND LOAD
* INTER-ORBIT SHUTTLES.
*
*
STA,42/ARR-LLO,1,1,D,B*             ARRIVE AT LLO LOADED WITH CARGO
ACT,42,43,CO,0*
QUE,43/UNLODOCK,0,,D,F*             LLO UNLOADING DOCK
VAS,43,2,CO,0*                      FLAG THE SHIP AS UNLOADED
ACT,43,44,UN,13,9/UNLO-LLO,1*       UNLOAD THE SHIP
STA,44/SHIP-UNLO,1,1,D,B*           SHIP IS UNLOADED
ACT,44,45,CO,0*
QUE,45/SERV-FAC,0,,D,F*             LLO SERVICE FACILITY
ACT,45,46,UN,14,10/SERV-LLO,1*      SERVICE THE SHIP
STA,46/GO-L2?,1,1,P,B*              WILL THE SHIP GO TO L2?
VAS,46,9,UF,45*                     (GET PROBABILITIES)
ACT,46,47,CO,0,,,5*                 (DO NOT GO TO L2)
STA,47/LO-SHIP,1,1,D,B*             SHIP NEEDS TO BE LOADED
ACT,47,48,CO,0*
QUE,48/SHIPS-LLO,0,,D,F,,,,58*      SHIPS WAITING TO BE LOADED
VAS,48,2,CO,1*                      FLAG THE SHIP AS LOADED
ACT,46,49,CO,0,,,6*                 (GO TO L2)
STA,49/LO-UNLO?,1,1,P,B*            WILL THE SHIP BE LOADED OR UNLOADED?
VAS,49,9,UF,46*                     (GET PROBABILITIES)
ACT,49,50,CO,0,,DIBH H HHHH H       (GO TO L2 LOADED)
STA,50/LOAD-SHIP,1,1,D,B*           LOAD THE SHIP WITH MISC CARGO FOR L2
ACT,50,51,CO,0*
QUE,51/LOADDOC2,0,,D,F*             LLO LOADING DOCK TWO
VAS,51,2,CO,1*                      FLAG THE SHIP AS LOADED
ACT,51,52,UN,16,12/LOAD2-LLO,1*     LOAD THE SHIP
STA,52/L2-LOAD,1,1,D,B*             SEND THE SHIP TO L2 LOADED
VAS,52,9,UF,16*
ACT,52,64,AT,4*                     (L2)
ACT,49,53,UF,17,,,6*                (GO TO L2 UNLOADED)
STA,53/L2-UNLO,1,1,D,B*             SEND THE SHIP TO L2 UNLOADED
ACT,53,64,AT,4*                     (L2)
STA,54/LLV-LAUN,1,1,D,B*            LUNAR LAUNCH VEHICLE (LLV) LAUNCHES
ACT,54,54,UN,11*                    TIME BETWEEN LLV LAUNCHES
ACT,54,55,CO,0*
STA,55/PRE-CARGO,1,1,D,B*           COLLECT ALL THE LLV CARGOS
ACT,55,56,UN,12*                    PREPARE THE NEXT SHIP'S CARGO
STA,56/CARGO-PRE,1,1,D,B*           CARGO IS PREPARED
ACT,56,57,CO,0*
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QUE,57/CARGO-LLO,0,,D,F,,,,58*        STORE THE SHIP'S CARGO
SEL,58/LOADDOC1,ASM,,B/1,,48,57*      LLO LOADING DOCK
ACT,58,59,UN,15,11/LOAD1-LLO,1*       LOAD THE SHIP
STA,59/LLO-DES?,1,1,P,B*              WHAT IS THE SHIP'S DESTINATION?
VAS,59,9,UF,47*                       (GET PROBABILITIES)
ACT,59,60,UF,12,,,5*                  (L5)
STA,60/LLO-L5,1,1,D,B*                LLO TO L5
ACT,60,117,AT,4*
ACT,59,61,UF,13,,,6*                  (L4)
STA,61/LLO-L4,1,1,D,B*                LLO TO L4
ACT,61,83,AT,4*
ACT,59,62,UF,14,,,7*                  (LEO)
STA,62/LLO-LEO,1,1,D,B*               LLO TO LEO
ACT,62,1,AT,4*
ACT,59,63,UF,15,,,8*                  (GEO)
STA,63/LLO-GEO,1,1,D,B*               LLO TO GEO
ACT,63,19,AT,4*
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*  UNSTABLE LAGRANGIAN POINT TWO (L2)
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* AT THE UNSTABLE LAGRANGIAN POINT TWO THERE IS A MASS CATCHER TO
* CAPTURE PACKETS OF LUNAR ORE THAT IS SENT UP TO L2 FROM THE LUNAR
* SURFACE BY A MASS DRIVER.  SINCE THE MASS DRIVER COULD "LAUNCH"
* 20 KG. PACKETS EVERY SECOND, THE MODEL WAS MODIFIED TO HAVE THE
* "PACKETS" BE EQUAL IN MASS TO THE MAXIMUM CAPACITY (METRIC TONS) OF
* AN INTER-ORBIT SHUTTLE SO AS TO NOT OVERLY COMPLICATE THE MODEL.
*
* THERE IS ALSO A SMALL SPACE STATION AT L2 TO PROVIDE FACILITIES
* FOR A CREW OF WORKERS WHO PREPARE THE LUNAR ORE FOR SHIPMENT TO
* L5.  WHILE EMPTY INTER-ORBIT SHUTTLES CAN COME FROM SEVERAL
* LOCATIONS AND INTER-ORBIT SHUTTLES THAT ARE LOADED WITH LUNAR
* ORE CAN GO TO L5, ALL OTHER INTER-ORBIT SHUTTLES MUST GO THROUGH
* LLO.  THE SPACE STATION ALSO HAS THE FACILITIES TO UNLOAD, SERVICE
* (MINIMUM), AND LOAD INTER-ORBIT SHUTTLES.
*
*
STA,64/LO-UNLO?,1,1,A,B*              ARRIVE AT L2, IS SHIP
*                                     LOADED/UNLOADED?
ACT,64,65,CO,0,,,,A2.GT.0*            (LOADED)
STA,65/LOADED,1,1,D,B*                SHIP IS LOADED WITH CARGO
ACT,65,66,CO,0*
QUE,66/UNLODOCK,0,,D,F*               L2 UNLOADING DOCK
VAS,66,2,CO,0*                        FLAG THE SHIP AS UNLOADED
ACT,66,67,UN,19,13/UNLO-L2,1*         UNLOAD THE SHIP
STA,67/SHIP-UNLO,1,1,D,B*             SHIP IS UNLOADED OF MISC CARGO
ACT,67,69,CO,0*
ACT,64,68,CO,0,,,,A2.LE.0*            (UNLOADED)
STA,68/UNLOADED,1,1,D,B*              SHIP ARRIVES AT L2 UNLOADED
ACT,68,69,CO,0*
STA,69/SERV-SHIP,1,1,D,B*             SHIP NEEDS SERVICING
ACT,69,70,CO,0*
QUE,70/SERV-FAC,0,,D,F*               L2 SERVICE FACILITY
ACT,70,71,UN,20,14/SERV-L2,1*         SERVICE THE SHIP
STA,71/CARGO?,1,1,P,B*                WHAT TYPE OF CARGO?
VAS,71,9,UF,48*                       (GET PROBABILITIES)
ACT,71,72,CO,0,,,5*                   (ORE)
STA,72/ORE,1,1,D,B*                   THE CARGO IS LUNAR ORE
ACT,72,73,CO,0*
QUE,73/SHIPS-L2,0,,D,F,,,,81*         SHIPS WAITING TO BE LOADED
VAS,73,2,CO,1,3,CO,1*                 FLAG THE SHIP AS LOADED WITH ORE
ACT,71,74,CO,0,,,6*                   (MISC)
STA,74/MISC,1,1,D,B*                  MISC CARGO
ACT,74,75,CO,0*
QUE,75/LOADDOC2,0,,D,F*               L2 LOADING DOCK TWO
VAS,75,2,CO,1*                        FLAG THE SHIP AS LOADED WITH MISC
*                                     CARGO
ACT,75,76,UN,22,16/LOAD2-L2,1*        LOAD THE SHIP
STA,76/GO-TO-LLO,1,1,D,B*             SEND MISC CARGO TO LLO
VAS,76,9,UF,19*
ACT,76,42,AT,4*                       (LLO)
STA,77/MASS-DRIVER,1,1,D,B*           MASS DRIVER
ACT,77,77,UN,17*                      TIME BETWEEN "LAUNCHES" FROM THE MOON
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ACT,77,78,CO,0*
STA,78/MASS-CATCHER,1,1,D,B*        MASS CATCHER, COLLECT ALL THE
*                                   MATERIAL
ACT,78,79,UN,18*                    PREPARE THE NEXT SHIP'S CARGO
STA,79/CARGO-PRE,1,1,D,B*           CARGO IS PREPARED
ACT,79,80,CO,0*
QUE,80/CARGO-L2,0,,D,F,,,,81*       STORE THE SHIP'S CARGO (ORE)
SEL,81/LOADDOC1,ASM,,B/1,,73,80*    L2 LOADING DOCK ONE
ACT,81,82,UN,21,15/LOAD1-L2,1*      LOAD THE SHIP
STA,82/GO-TO-L5,1,1,D,B*            SEND LUNAR MATERIAL TO L5
VAS,82,9,UF,18*
ACT,82,117,AT,4*                    (L5)
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*  STABLE LAGRANGIAN POINT FOUR (L4)
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* AT THE STABLE LAGRANGIAN POINT FOUR THERE IS A LARGE SPACE COLONY
* (APPROXIMATE POPULATION = 10,000 PEOPLE).  THE MAIN ACTIVITIES FOR
* THE SPACE COLONY'S POPULATION IS TO TRANSFORM RAW MATERIALS FROM
* L5 INTO MORE SPACE COLONIES AT L4 AND SSPS PARTS FOR CONSTRUCTION
* OF SSPS'S AT GEO.  THE SPACE COLONY ALSO HAS THE FACILITIES TO
* UNLOAD, SERVICE (MINIMUM), AND LOAD INTER-ORBIT SHUTTLES.
*
*
STA,83/LO-UNLO?,1,1,A,B*             ARRIVE AT L4, IS SHIP
*                                    LOADED/UNLOADED?
ACT,83,84,CO,0,,,,A2.LE.0*           (UNLOADED)
STA,84/UNLOADED,1,1,D,B*             SHIP ARRIVES AT L4 UNLOADED
ACT,84,92,CO,0*
ACT,83,85,CO,0,,,,A2.GT.0*           (LOADED)
STA,85/CARGO?,1,1,A,B*               WHAT TYPE OF CARGO?
ACT,85,86,CO,0,,,,A3.LE.0*           (MISC)
STA,86/MISC-L4,1,1,D,B*              MISC CARGO
ACT,86,87,CO,0*
QUE,87/UNLODOC1,0,,D,F*              L4 UNLOADING DOCK ONE
VAS,87,2,CO,0*                       FLAG THE SHIP AS UNLOADED
ACT,87,88,UN,25,17/UNL1-L4,1*        UNLOAD THE SHIP
STA,88/SHIP-UNLO,1,1,D,B*            SHIP IS UNLOADED OF MISC CARGO
ACT,88,92,CO,0*
ACT,85,89,CO,0,,,,A3.GT.0*           (RAW MATERIALS)
STA,89/RAW-L4,1,1,D,B*               THE CARGO IS RAW MATERIALS
ACT,89,90,CO,0*
QUE,90/UNLODOC2,0,,D,F*              L4 UNLOADING DOCK TWO
VAS,90,2,CO,0,3,CO,0*                FLAG THE SHIP AS UNLOADED
ACT,90,91,UN,26,18/UNL2-L4,1*        UNLOAD THE SHIP OF RAW MATERIALS
STA,91/SEPARATE,1,1,D,B*             SEPARATE CARGO FROM SHIP
ACT,91,92,CO,0*
STA,92/SERV-SHIP,1,1,D,B*            SHIP NEEDS SERVICING
ACT,92,93,CO,0*
QUE,93/SERV-FAC,0,,D,F*              L4 SERVICE FACILITY
ACT,93,103,UN,27,19/SERV-L4,1*       SERVICE THE SHIP
ACT,91,94,CO,0*
STA,94/WHERE?,1,1,P,B*               WHERE WILL RAW MATERIALS BE USED?
VAS,94,1,CO,0,9,UF,49*               (GET PROBABILITIES)
ACT,94,95,CO,0,,,5*                  (SSPS)
STA,95/SSPS,1,1,D,B*                 USE RAW MATERIALS FOR SSPS
ACT,95,96,CO,0*
QUE,96/SSPS-STOR,0,,D,F*             RAW MATERIALS STORAGE FOR SSPS
ACT,96,97,UN,23,21/BUILD-SSPS,1*     PUT TOGETHER SSPS PARTS
STA,97/SSPS-BUILD,1,1,D,B*           FINISHED SSPS PARTS
ACT,97,98,CO,0*
QUE,98/CARGO-L4,0,,D,F,,,,110*       STORE THE SHIP'S CARGO (SSPS PARTS)
ACT,94,99,CO,0,,,6*                  (L4 COLONIES)
STA,99/L4-COLONY,1,1,D,B*            USE RAW MATERIALS FOR COLONIES AT
*                                    L4
ACT,99,100,CO,0*
QUE,100/COL-STOR,0,,D,F*             RAW MATERIALS STORAGE FOR COLONIES
ACT,100,101,UN,24,22/BUILD-COL,1*    PUT TOGETHER COLONY PARTS
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STA,101/COL-BUILD,500,500,D,B*      BUILD A COMPLETE COLONY
ACT,101,102,UF,37*
STA,102/NEW-COLONY,1,1,D,B*         KEEP TRACK OF NEW COLONIES
STA,103/LO-UNLO?,1,1,P,B*           WILL THE SHIP BE LOADED OR UNLOADED?
VAS,103,9,UF,50*                    (GET PROBABILITIES)
ACT,103,104,UF,24,,,5*              (UNLOADED)
STA,104/GO-TO-L2,1,1,D,B*           SEND THE SHIP TO L2 UNLOADED
ACT,104,64,AT,4*                    (L2)
ACT,103,105,CO,0,,,6*               (LOADED)
STA,105/CARGO?,1,1,P,B*             WHAT TYPE OF CARGO?
VAS,105,9,UF,51*                    (GET PROBABILITIES)
ACT,105,106,CO,0,,,5*               (MISC)
STA,106/MISC,1,1,D,B*               MISC CARGO
ACT,106,107,CO,0*
QUE,107/LOADDOC1,0,,D,F*            L4 LOADING DOCK ONE
VAS,107,2,CO,1*                     FLAG THE SHIP AS LOADED WITH MISC
*                                   CARGO
ACT,107,112,UN,28,20/LOAD1-L4,1*    LOAD THE SHIP
ACT,105,108,CO,0,,,6*               (SSPS PARTS)
STA,108/SSPS,1,1,D,B*               THE CARGO IS SSPS PARTS
ACT,108,109,CO,0*
QUE,109/SHIPS-L4,0,,D,F,,,,110*     SHIPS WAITING TO BE LOADED
VAS,109,2,CO,1,3,CO,1*              FLAG THE SHIP AS LOADED WITH SSPS
*                                   PARTS
SEL,110/LOADDOC2,ASM,,B/1,,98,109*  L4 LOADING DOCK TWO
ACT,110,111,UN,29,23/LOAD2-L4,1*    LOAD THE SHIP
STA,111/GO-TO-GEO,1,1,D,B*          SEND SSPS PARTS TO GEO
VAS,111,9,UF,25*
ACT,111,19,AT,4*                    (GEO)
STA,112/L4-DEST?,1,1,P,B*           WHAT IS THE SHIP'S DESTINATION?
VAS,112,9,UF,52*                    (GET PROBABILITIES)
ACT,112,113,UF,20,,,5*              (LLO)
STA,113/L4-LLO,1,1,D,B*             L4 TO LLO
ACT,113,42,AT,4*
ACT,112,114,UF,21,,,6*              (L5)
STA,114/L4-L5,1,1,D,B*              L4 TO L5
ACT,114,117,AT,4*
ACT,112,115,UF,22,,,7*              (LEO)
STA,115/L4-LEO,1,1,D,B*             L4 TO LEO
ACT,115,1,AT,4*
ACT,112,116,UF,23,,,8*              (GEO)
STA,116/L4-GEO,1,1,D,B*             L4 TO GEO
ACT,116,19,AT,4*
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*  STABLE LAGRANGIAN POINT FIVE (L5)
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* AT THE STABLE LAGRANGIAN POINT FIVE THERE IS A LARGE SPACE COLONY
* (APPROXIMATE POPULATION = 10,000 PEOPLE).  THE MAIN ACTIVITIES FOR
* THE SPACE COLONY'S POPULATION IS TO TRANSFORM ASTEROIDAL ORE AND
* LUNAR ORE INTO "PURE" METALS AND NON-METALS.  THE PROCESSED RAW
* MATERIALS AND SLAG WILL BE USED TO BUILD MORE SPACE COLONIES AT L5,
* TO BUILD MORE SPACE COLONIES AT L4, TO BUILD SSPS PARTS AT L4 FOR
* CONSTRUCTION OF SSPS'S AT GEO, AND AS FUEL FOR THE INTER-ORBIT
* SHUTTLES AND INTER-PLANETARY SPACE VEHICLES (IPSV).  THE IPSV, A
* MASS-DRIVER POWERED SPACE VEHICLE, RETRIEVE ASTEROIDS EITHER FROM
* THE COLLECTION OF EARTH ORBIT CROSSING ASTEROIDS OR FROM THE ASTEROID
* BELT.  THE SPACE COLONY ALSO HAS THE FACILITIES TO UNLOAD, SERVICE
* (NORMAL AND MAJOR REPAIRS), AND LOAD INTER-ORBIT SHUTTLES.  THE
* FACILITIES TO UNLOAD, SERVICE, AND LOAD INTER-PLANETARY SPACE
* VEHICLES ARE ALSO AT L5 BUT ARE NOT INCORPORATED INTO THE MODEL.
*
*
STA,117/CARGO?,1,1,A,B*               ARRIVE AT L5, WHAT TYPE OF CARGO?
ACT,117,118,CO,0,,,,A3.LE.0*          (MISC)
STA,118/MISC-L5,1,1,D,B*              MISC CARGO
ACT,118,119,CO,0*
QUE,119/UNLODOC1,0,,D,F*              L5 UNLOADING DOCK ONE
VAS,119,2,CO,0*                       FLAG THE SHIP AS UNLOADED
ACT,119,120,UN,35,24/UNL1-L5,1*       UNLOAD THE SHIP
STA,120/SHIP-UNLO,1,1,D,B*            SHIP IS UNLOADED OF MISC CARGO
ACT,120,124,CO,0*
ACT,117,121,CO,0,,,,A3.GT.0*          (ORE)
STA,121/ORE-L5,1,1,D,B*               THE CARGO IS LUNAR ORE
ACT,121,122,CO,0*
QUE,122/UNLODOC2,0,,D,F*              L5 UNLOADING DOCK TWO
VAS,122,2,CO,0,3,CO,0*                FLAG THE SHIP AS UNLOADED
ACT,122,123,UN,36,25/UNL2-L5,1*       UNLOAD THE SHIP OF LUNAR ORE
STA,123/SEPARATE,1,1,D,B*             SEPARATE CARGO FROM SHIP
ACT,123,124,CO,0*
STA,124/OLD?,1,1,A,B*                 IS THE SHIP'S SERVICE LIFE OVER?
VAS,124,9,UF,35*                      UPDATE TIME IN SERVICE
ACT,124,125,UF,34,,,,A10.GT.0*        (OLD)
STA,125/SHIP-OLD,1,1,D,B*             SHIP'S SERVICE LIFE IS OVER
ACT,124,126,CO,0,,,,A10.LE.0*         (NOT OLD)
STA,126/REPAIRS?,1,1,P,B*             DOES THE SHIP NEED MAJOR REPAIRS?
VAS,126,9,UF,53*                      (GET PROBABILITIES)
ACT,126,127,CO,0,,,5*                 (NORMAL)
STA,127/NORMAL,1,1,D,B*               SHIP NEEDS NORMAL SERVICING
ACT,127,128,CO,0*
QUE,128/SER-FAC1,0,,D,F*              L5 SERVICE FACILITY ONE
ACT,128,129,UN,37,26/SERV1-L5,1*      SERVICE THE SHIP
STA,129/SHIP-SE1,1,1,D,B*             SHIP IS SERVICED
ACT,129,155,CO,0*
ACT,126,130,CO,0,,,6*                 (MAJOR)
STA,130/DAMAGE?,1,1,P,B*              SHIP NEEDS MAJOR REPAIRS.
*                                     IS THE SHIP REPAIRABLE?
VAS,130,9,UF,54*                      (GET PROBABILITIES)
ACT,130,131,UF,32,,,5*                (REPAIRABLE)
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STA,131/FIXABLE,1,1,D,B*              SHIP NEEDS MAJOR REPAIRS BUT IS
*                                     REPAIRABLE
ACT,131,132,CO,0*
QUE,132/SER-FAC2,0,,D,F*              L5 SERVICE FACILITY TWO
ACT,132,133,UN,38,27/SERV2-L5,1*      SERVICE THE SHIP
STA,133/SHIP-SE2,1,1,D,B*             SHIP IS SERVICED
ACT,133,155,CO,0*
ACT,130,134,UF,33,,,6*                (NOT REPAIRABLE)
STA,134/RETIRE,1,1,D,B*               RETIRE THE SHIP FROM SERVICE DUE TO
*                                     DAMAGE
ACT,123,135,CO,0*
QUE,135/PROCESS1,0,,D,F*              L5 PROCESSING PLANT ONE
*                                     (LUNAR ORE)
ACT,135,136,UN,32,28/PROC1-L5,1*      PROCESS THE LUNAR ORE INTO "PURE"
*                                     METALS AND NON-METALS
STA,136/LUNAR-ORE,1,1,D,B*            LUNAR ORE IS PROCESSED
ACT,136,146,CO,0*
STA,137/ASTEROID,1,1,D,B*             AN ASTEROID ARRIVES AT L5
VAS,137,1,UF,39,2,CO,0*               GET THE MASS OF THE ASTEROID
ACT,137,137,UN,30*                    GO GET NEXT ASTEROID
ACT,137,138,CO,0*
QUE,138/ASTER-STO,0,,D,F,,,,141*      ASTEROID STORAGE FACILITY
STA,139/FREE-MINER,1,1,D,B*           FREE THE ASTEROID MINER SO THAT IT
*                                     CAN BE USED ON THE NEXT ASTEROID
VAS,139,1,CO,0,2,CO,0*                FLAG THE MINER AS FREE
ACT,139,140,CO,0*
QUE,140/MINER,1,1,D,F,,,,141*         THERE IS ONE AND ONLY ONE ASTEROID
*                                     MINER WHICH IS ASSIGNED TO AN
*                                     ASTEROID ONLY WHEN THE PREVIOUS
*                                     ASTEROID HAS BEEN COMPLETELY MINED
SEL,141/ASTER-MINER,ASM,,B/1,,138,140*   ASTEROID MINING FACILITY
ACT,141,142,UN,31,29/MINE-L5,1*       START MINING THE ASTEROID
STA,142/FINISH?,1,1,A,B*              HAVE WE FINISHED MINING THE ASTEROID?
VAS,142,2,UF,59*                      INCREMENT A COUNTER WHICH DETERMINES
*                                     IF AN ASTEROID IS COMPLETELY MINED
ACT,142,142,UN,31,,,,A2.LE.A1*        (NO, CONTINUE MINING)
ACT,142,139,CO,0,,,,A2.GT.A1*         (YES, FREE MINER)
ACT,142,143,CO,0,,,,A2.GE.1*          TRANSFER MINED ASTEROIDAL ORE TO
*                                     PROCESSING PLANT
STA,143/MINED-ORE,1,1,D,B*            MINED ASTEROIDAL ORE IS READY TO BE
*                                     PROCESSED
ACT,143,144,CO,0*
QUE,144/PROCESS2,0,,D,F*              L5 PROCESSING PLANT TWO
*                                     (ASTEROIDAL ORE)
ACT,144,145,UN,33,30/PROC2-L5,1*      PROCESS THE ASTEROIDAL ORE INTO
*                                     "PURE" METALS AND NON-METALS
STA,145/ASTER-ORE,1,1,D,B*            ASTEROIDAL ORE IS PROCESSED
ACT,145,146,CO,0*
STA,146/WHERE-HOW?,1,1,P,B*           WHERE/HOW WILL THE RAW MATERIALS BE
*                                     USED?
VAS,146,1,CO,0,9,UF,56*               (GET PROBABILITIES)
ACT,146,147,CO,0,,,5*                 (SLAG)
STA,147/SLAG,1,1,D,B*                 THE WASTE PRODUCTS OR SLAG FROM THE
*                                     PROCESSING OF LUNAR AND ASTEROIDAL
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*                                      ORE COULD BE USED AS FUEL FOR THE
*                                      MASS DRIVER PROPELLED SPACE VEHICLES
*                                      WHICH RETRIEVE ASTEROIDS.
ACT,146,148,CO,0,,,6*                  (L5 COLONIES)
STA,148/L5-COLONY,1,1,D,B*             USE THE RAW MATERIALS FOR COLONIES AT
*                                      L5
ACT,148,149,CO,0*
QUE,149/COL-STOR,0,,D,F*               RAW MATERIALS STORAGE FOR COLONIES
ACT,149,150,UN,34,31/BUILD-COL,1*      PUT TOGETHER COLONY PARTS
STA,150/COL-BUILD,500,500,D,B*         BUILD A COMPLETE COLONY
ACT,150,151,UF,38*
STA,151/NEW-COLONY,1,1,D,B*            KEEP TRACK OF NEW COLONIES
ACT,146,152,CO,0,,,7*                  (L4 COLONIES AND SSPS PARTS)
STA,152/L4-RAW,1,1,D,B*                SEND THE RAW MATERIALS TO L4 TO BE
*                                      USED FOR COLONIES AND SSPS PARTS
ACT,152,153,US,1*                      (IS A NEW SHIP NEEDED?)
QUE,153/CARGO-L5,0,,D,F,,,,161*        STORE THE SHIP'S CARGO (RAW MATERIALS
*                                      FOR L4)
STA,154/GENERATE,1,1,A,B*              GENERATE THE FIRST FIVE INTER-ORBIT
*                                      SHUTTLES USED IN THE MODEL.
VAS,154,9,US,2*                        (INCREMENT SHIP NUMBER)
ACT,154,154,CO,0,,,,A1.LT.5*           GENERATE SHIPS
ACT,154,155,CO,0,,,,A1.LE.5*           PUT SHIPS INTO THE NETWORK
STA,155/LO-UNLO?,1,1,P,B*              WILL THE SHIP BE LOADED OR UNLOADED?
VAS,155,9,UF,55*                       (GET PROBABILITIES)
ACT,155,156,UF,30,,,5*                 (UNLOADED)
STA,156/GO-TO-L2,1,1,D,B*              SEND THE SHIP TO L2 UNLOADED
ACT,156,64,AT,4*                       (L2)
STA,157/NEW-SHIP,1,1,D,B*              NEW SHIPS ENTER THE NETWORK AT THIS
*                                      NODE BASED ON A DECISION BY THE
*                                      SUBROUTINE US THAT A SHIP IS NEEDED.
*                                      A SHIP IS NEEDED WHENEVER THE SHIP'S
*                                      QUEUE (NODE 160) IS EMPTY AND A CARGO
*                                      IS APPROACHING THE STORAGE QUEUE
*                                      (NODE 153) AT THE L5 LOADING DOCK
*                                      ONE.
ACT,155,158,CO,0,,,6*                  (LOADED)
ACT,157,159,CO,0*
STA,158/CARGO?,1,1,P,B*                WHAT TYPE OF CARGO?
VAS,158,9,UF,57*                       (GET PROBABILITIES)
ACT,158,159,CO,0,,,5*                  (RAW MATERIALS)
STA,159/RAW,1,1,D,B*                   THE CARGO IS RAW MATERIALS
ACT,159,160,CO,0*
QUE,160/SHIPS-L5,0,,D,F,,,,161*        SHIPS WAITING TO BE LOADED
VAS,160,2,CO,1,3,CO,1*                 FLAG THE SHIP AS LOADED WITH RAW
*                                      MATERIALS
SEL,161/LOADDOC1,ASM,,B/1,,153,160*     L5 LOADING DOCK ONE
ACT,161,162,UN,39,32/LOAD1-L5,1*       LOAD THE SHIP
STA,162/GO-TO-L4,1,1,D,B*              SEND RAW MATERIALS TO L4
VAS,162,9,UF,31*
ACT,162,83,AT,4*                       (L4)
ACT,158,163,CO,0,,,6*                  (MISC)
STA,163/MISC,1,1,D,B*                  MISC CARGO
ACT,163,164,CO,0*
```

```
QUE,164/LOADDOC2,0,,D,F*            L5 LOADING DOCK TWO
VAS,164,2,CO,1*                     FLAG THE SHIP AS LOADED WITH MISC
*                                   CARGO
ACT,164,165,UN,40,33/LOAD2-L5,1*    LOAD THE SHIP
STA,165/L5-DEST?,1,1,P,B*           WHAT IS THE SHIP'S DESTINATION?
VAS,165,9,UF,58*                    (GET PROBABILITIES)
ACT,165,166,UF,26,,,5*              (L4)
STA,166/L5-L4,1,1,D,B*              L5 TO L4
ACT,166,83,AT,4*
ACT,165,167,UF,27,,,6*              (LLO)
STA,167/L5-LLO,1,1,D,B*             L5 TO LLO
ACT,167,42,AT,4*
ACT,165,168,UF,28,,,7*              (LEO)
STA,168/L5-LEO,1,1,D,B*             L5 TO LEO
ACT,168,1,AT,4*
ACT,165,169,UF,29,,,8*              (GEO)
STA,169/L5-GEO,1,1,D,B*             L5 TO GEO
ACT,169,19,AT,4*
*
*
*
```

```
* INITIALIZE THE Q-GERT NETWORK.
*
*
SOU,170,0,1,D,M*                    INITIALIZE THE NETWORK
ACT,170,9,CO,0*                     THE ARRIVAL OF THE FIRST HLV AT LEO
ACT,170,54,CO,0*                    THE ARRIVAL OF THE FIRST LLV AT LLO
ACT,170,77,CO,0*                    THE ARRIVAL OF THE FIRST MASS DRIVER
*                                   "PACKET" AT L2
ACT,170,137,CO,0*                   THE ARRIVAL OF THE FIRST ASTEROID
*                                   AT L5
ACT,170,154,CO,0*                   INITIALIZE THE "PRODUCTION" OF THE
*                                   FIRST FIVE INTER-ORBIT SHUTTLES
*
*
*
```

```
*  PARAMETER SETS USED IN THE MODEL
*
*
*
*  TIMES TO ACCOMPLISH ACTIVITIES AT NODES IN THE NETWORK
*
*
*                                   LOW EARTH ORBIT (LEO)
*
PAR,1,,10.0,20.0*                   TIME BETWEEN HLV LAUNCHES
PAR,2,,1.0,2.0*                     TIME TO PREPARE A CARGO
PAR,3,,1.0,2.0*                     TIME TO UNLOAD A SHIP
PAR,4,,1.0,2.0*                     TIME TO SERVICE A SHIP
PAR,5,,1.0,2.0*                     TIME TO LOAD A SHIP
*
*
*                                   GEOSTATIONARY EARTH ORBIT (GEO)
*
PAR,6,,25.0,35.0*                   TIME TO BUILD A FRACTION OF A
*                                   SATELLITE SOLAR POWER SYSTEM (SSPS),
*                                   I.E., MASS EQUIVILANT TO A SHIP'S
*                                         CARGO
PAR,7,,1.0,2.0*                     TIME TO UNLOAD A SHIP - SSPS PARTS
PAR,8,,1.0,2.0*                     TIME TO UNLOAD A SHIP - MISC CARGO
PAR,9,,1.0,2.0*                     TIME TO SERVICE A SHIP
PAR,10,,1.0,2.0*                    TIME TO LOAD A SHIP
*
*
*                                   LOW LUNAR ORBIT (LLO)
*
PAR,11,,10.0,20.0*                  TIME BETWEEN LUNAR LV LAUNCHES
PAR,12,,1.0,2.0*                    TIME TO PREPARE A CARGO
PAR,13,,1.0,2.0*                    TIME TO UNLOAD A SHIP
PAR,14,,1.0,2.0*                    TIME TO SERVICE A SHIP
PAR,15,,1.0,2.0*                    TIME TO LOAD A SHIP - MISC CARGO
PAR,16,,1.0,2.0*                    TIME TO LOAD A SHIP - FOR L2
*
*
*                                   UNSTABLE LAGRANGIAN POINT TWO (L2)
*
PAR,17,,5.0,5.5*                    TIME BETWEEN MASS DRIVER "LAUNCHES"
PAR,18,,1.0,2.0*                    TIME TO PREPARE A CARGO
PAR,19,,1.0,2.0*                    TIME TO UNLOAD A SHIP
PAR,20,,1.0,2.0*                    TIME TO SERVICE A SHIP
PAR,21,,1.0,2.0*                    TIME TO LOAD A SHIP - LUNAR ORE
PAR,22,,1.0,2.0*                    TIME TO LOAD A SHIP - MISC CARGO
*
*
*                                   STABLE LAGRANGIAN POINT FOUR (L4)
*
PAR,23,,25.0,35.0*                  TIME TO BUILD SSPS PARTS,
*                                   I.E., MASS EQUIVILANT TO A SHIP'S
*                                         CARGO
PAR.24,,7.0,3.0*                    TIME TO BUILD A FRACTION OF A COLONY,
```

```
*                                   I.E., MASS EQUIVILANT TO A SHIP'S
*                                         CARGO
PAR,25,,1.0,2.0*                    TIME TO UNLOAD A SHIP - MISC CARGO
PAR,26,,1.0,2.0*                    TIME TO UNLOAD A SHIP - RAW MATERIALS
PAR,27,,1.0,2.0*                    TIME TO SERVICE A SHIP
PAR,28,,1.0,2.0*                    TIME TO LOAD A SHIP - MISC CARGO
PAR,29,,1.0,2.0*                    TIME TO LOAD A SHIP - SSPS PARTS
*
*
*                                   STABLE LAGRANGIAN POINT FIVE (L5)
*
PAR,30,,1642.0,2008.0*              TIME BETWEEN ARRIVALS OF ASTEROIDS
PAR,31,,4.0,6.0*                    TIME TO TO MINE THE ASTEROID,
*                                   I.E., MASS EQUIVILANT TO A SHIP'S
*                                         CARGO
PAR,32,,4.0,6.0*                    TIME TO PROCESS LUNAR ORE,
*                                   I.E., MASS EQUIVILANT TO A SHIP'S
*                                         CARGO
PAR,33,,4.0,6.0*                    TIME TO PROCESS ASTEROIDAL ORE,
*                                   I.E., MASS EQUIVILANT TO A SHIP'S
*                                         CARGO
PAR,34,,7.0,8.0*                    TIME TO BUILD A FRACTION OF A COLONY,
*                                   I.E., MASS EQUIVILANT TO A SHIP'S
*                                         CARGO
PAR,35,,1.0,2.0*                    TIME TO UNLOAD A SHIP - MISC CARGO
PAR,36,,1.0,2.0*                    TIME TO UNLOAD A SHIP - LUNAR ORE
PAR,37,,1.0,2.0*                    TIME TO SERVICE A SHIP - NORMAL
PAR,38,,2.0,30.0*                   TIME TO SERVICE A SHIP - MAJOR
PAR,39,,1.0,2.0*                    TIME TO LOAD A SHIP - RAW MATERIALS
PAR,40,,1.0,2.0*                    TIME TO LOAD A SHIP - MISC CARGO
*
*
*
*  TRAVEL TIMES BETWEEN NODES IN THE NETWORK
*
*
*                                   LOW EARTH ORBIT (LEO)
*
PAR,41,,0.2,0.3*                    SHUTTLE TRAVELS FROM LEO TO GEO
*                                   -- LOADED
PAR,42,,5.0,7.0*                    SHUTTLE TRAVELS FROM LEO TO L5
*                                   -- LOADED
PAR,43,,5.0,7.0*                    SHUTTLE TRAVELS FROM LEO TO L4
*                                   -- LOADED
PAR,44,,5.0,7.0*                    SHUTTLE TRAVELS FROM LEO TO LLO
*                                   -- LOADED
PAR,45,,7.5,10.5*                   SHUTTLE TRAVELS FROM LEO TO L2
*                                   -- UNLOADED
*
*
*                                   GEOSTATIONARY EARTH ORBIT (GEO)
*
PAR,46,,0.2,0.3*                    SHUTTLE TRAVELS FROM GEO TO LEO
*                                   -- LOADED
```

```
PAR,47,,5.0,7.0*                  SHUTTLE TRAVELS FROM GEO TO L5
*                                 -- LOADED
PAR,48,,5.0,7.0*                  SHUTTLE TRAVELS FROM GEO TO LLO
*                                 -- LOADED
PAR,49,,5.0,7.0*                  SHUTTLE TRAVELS FROM GEO TO L4
*                                 -- LOADED
PAR,50,,5.0,7.0*                  SHUTTLE TRAVELS FROM GEO TO L4
*                                 -- UNLOADED
PAR,51,,7.5,10.0*                 SHUTTLE TRAVELS FROM GEO TO L2
*                                 -- UNLOADED
*
*
*                                 LOW LUNAR ORBIT (LLO)
*
PAR,52,,8.0,10.0*                 SHUTTLE TRAVELS FROM LLO TO L5
*                                 -- LOADED
PAR,53,,8.0,10.0*                 SHUTTLE TRAVELS FROM LLO TO L4
*                                 -- LOADED
PAR,54,,5.0,7.0*                  SHUTTLE TRAVELS FROM LLO TO LEO
*                                 -- LOADED
PAR,55,,5.0,7.0*                  SHUTTLE TRAVELS FROM LLO TO GEO
*                                 -- LOADED
PAR,56,,2.5,3.5*                  SHUTTLE TRAVELS FROM LLO TO L2
*                                 -- LOADED
PAR,57,,2.5,3.5*                  SHUTTLE TRAVELS FROM LLO TO L2
*                                 -- UNLOADED
*
*
*                                 UNSTABLE LAGRANGIAN POINT TWO (L2)
*
PAR,58,,10.5,13.5*                SHUTTLE TRAVELS FROM L2  TO L5
*                                 -- LOADED (LUNAR ORE)
PAR,59,,2.5,3.5*                  SHUTTLE TRAVELS FROM L2  TO LLO
*                                 -- LOADED
*
*
*                                 STABLE LAGRANGIAN POINT FOUR (L4)
*
PAR,60,,8.0,10.0*                 SHUTTLE TRAVELS FROM L4  TO LLO
*                                 -- LOADED
PAR,61,,16.0,20.0*                SHUTTLE TRAVELS FROM L4  TO L5
*                                 -- LOADED
PAR,62,,5.0,7.0*                  SHUTTLE TRAVELS FROM L4  TO LEO
*                                 -- LOADED
PAR,63,,5.0,7.0*                  SHUTTLE TRAVELS FROM L4  TO GEO
*                                 -- LOADED
PAR,64,,10.5,13.5*                SHUTTLE TRAVELS FROM L4  TO L2
*                                 -- UNLOADED
PAR,65,,5.0,7.0*                  SHUTTLE TRAVELS FROM L4  TO GEO
*                                 -- LOADED (SSPS PARTS)
*
*
*                                 STABLE LAGRANGIAN POINT FOUR (L5)
*
```

```
PAR,66,,16.0,20.0*                 SHUTTLE TRAVELS FROM L5  TO L4
*                                  -- LOADED
PAR,67,,8.0,10.0*                  SHUTTLE TRAVELS FROM L5  TO LLO
*                                  -- LOADED
PAR,68,,5.0,7.0*                   SHUTTLE TRAVELS FROM L5  TO LEO
*                                  -- LOADED
PAR,69,,5.0,7.0*                   SHUTTLE TRAVELS FROM L5  TO GEO
*                                  -- LOADED
PAR,70,,10.5,13.5*                 SHUTTLE TRAVELS FROM L5  TO L2
*                                  -- UNLOADED
PAR,71,,16.0,20.0*                 SHUTTLE TRAVELS FROM L5  TO L4
*                                  -- LOADED (RAW MATERIALS)
*
*
*
```

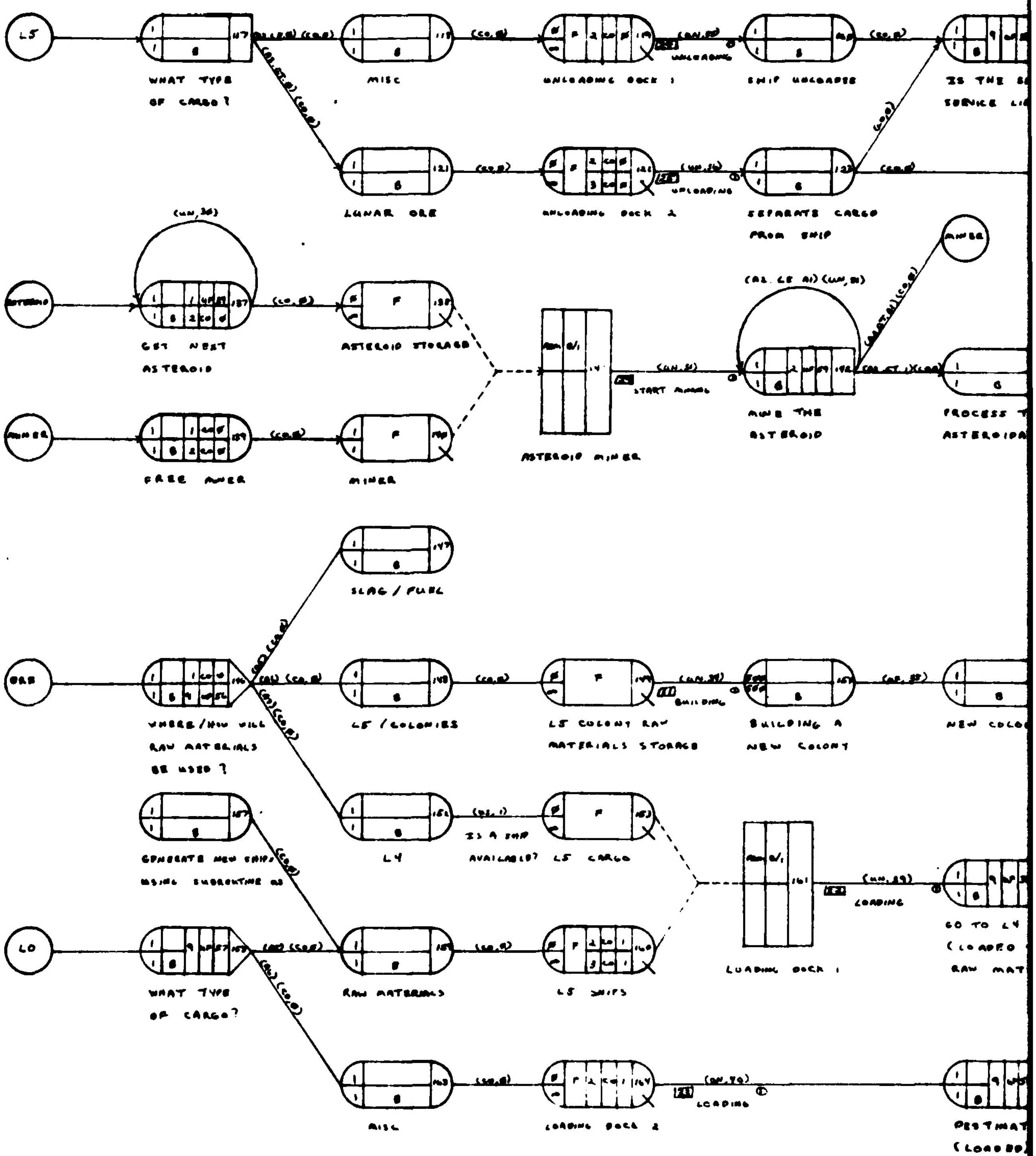
```
*  ATTRIBUTE LIST FOR AN INTER-ORBIT SPACE SHUTTLE
*
*
*     ATTRIBUTE            DESCRIPTION                  RANGE
*     ---------            -----------                  -----
*
*          1               SHUTTLE NUMBER               1.0 TO 500.0
*
*          2               UNLOADED / LOADED            0.0 / 1.0
*
*          3               MISC CARGO / RAW MATERIALS   0.0 / 1.0
*
*          4               TRAVEL TIME                  >= 0.0
*
*          5               PROBABILITY                  0.0 TO 1.0
*
*          6               PROBABILITY                  0.0 TO 1.0
*
*          7               PROBABILITY                  0.0 TO 1.0
*
*          8               PROBABILITY                  0.0 TO 1.0
*
*          9               DUMMY VARIABLE               0.0
*
*         10               KEEP / RETIRE SHIP           0.0 / 1.0
*
*         11               MARK TIME                    >= 0.0
*
*
*
*  ATTRIBUTE LIST FOR AN ASTEROID
*
*
*     ATTRIBUTE            DESCRIPTION                  RANGE
*     ---------            -----------                  -----
*
*          1               THE TOTAL NUMBER OF          >= 0.0
*                          SHUTTLE CARGOS IN AN
*                          ASTEROID
*
*          2               THE NUMBER OF SHUTTLE        >= 0.0
*                          CARGOS ALREADY MINED
*                          FROM AN ASTEROID
*
*          3               NOT USED                     0.0
*
*          4               NOT USED                     0.0
*
*          5               PROBABILITY                  0.0 TO 1.0
*
*          6               PROBABILITY                  0.0 TO 1.0
*
*          7               PROBABILITY                  0.0 TO 1.0
*
```

```
*             8           PROBABILITY                 0.0 TO 1.0
*
*             9           DUMMY VARIABLE              0.0
*
*            10           NOT USED                    0.0
*
*            11           MARK TIME                   >= 0.0
*
*
*
*  ATTRIBUTE LIST FOR ALL OTHER TRANSACTIONS
*
*
*    ATTRIBUTE            DESCRIPTION                 RANGE
*    ---------            -----------                 -----
*
*             1           NOT USED                    0.0
*
*             2           NOT USED                    0.0
*
*             3           NOT USED                    0.0
*
*             4           NOT USED                    0.0
*
*             5           PROBABILITY                 0.0 TO 1.0
*
*             6           PROBABILITY                 0.0 TO 1.0
*
*             7           PROBABILITY                 0.0 TO 1.0
*
*             8           PROBABILITY                 0.0 TO 1.0
*
*             9           DUMMY VARIABLE              0.0
*
*            10           NOT USED                    0.0
*
*            11           MARK TIME                   >= 0.0
*
*
*
FIN*
*EOR
```

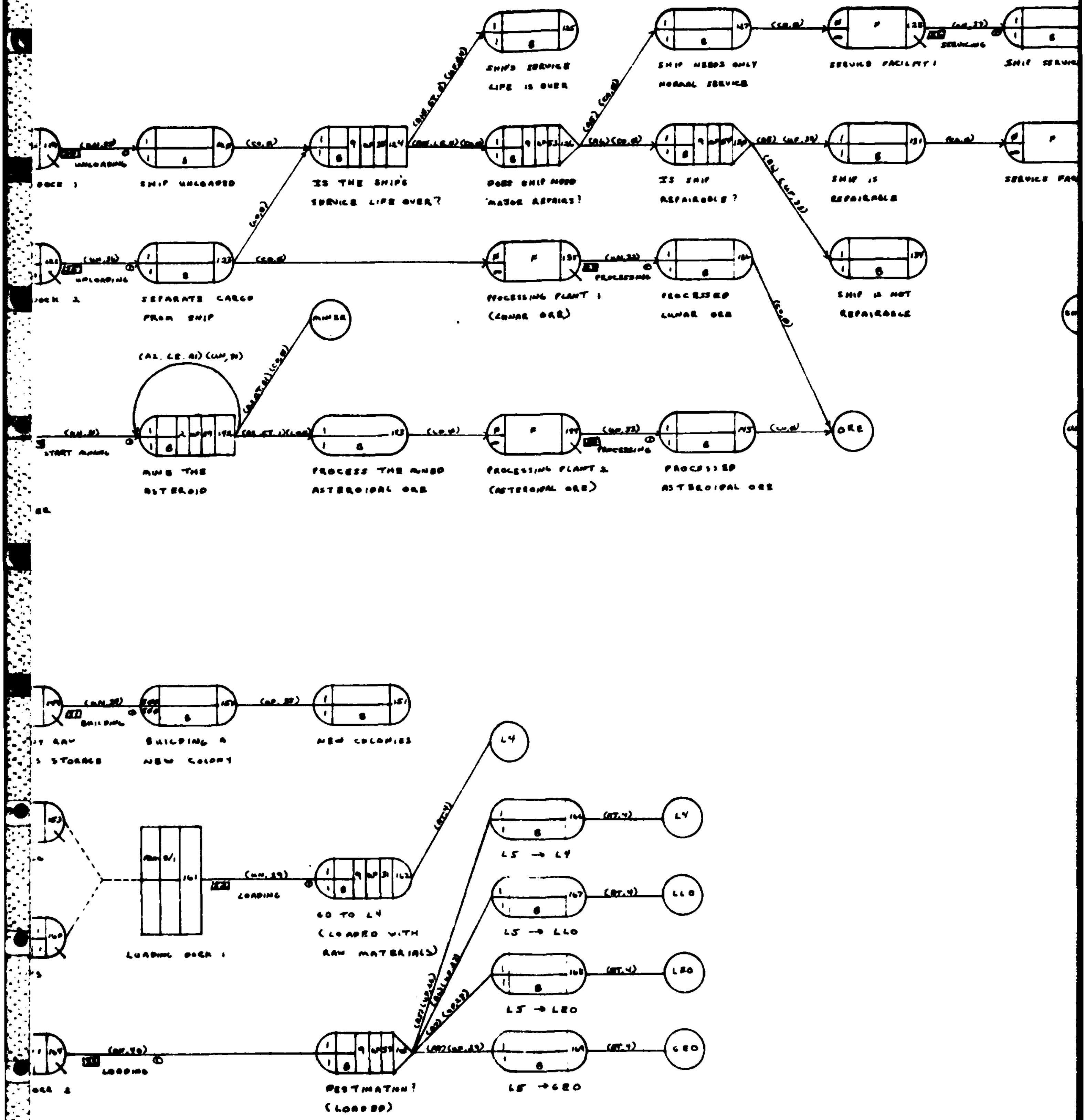
APPENDIX B

The SCMS Q-GERT Nodal Description

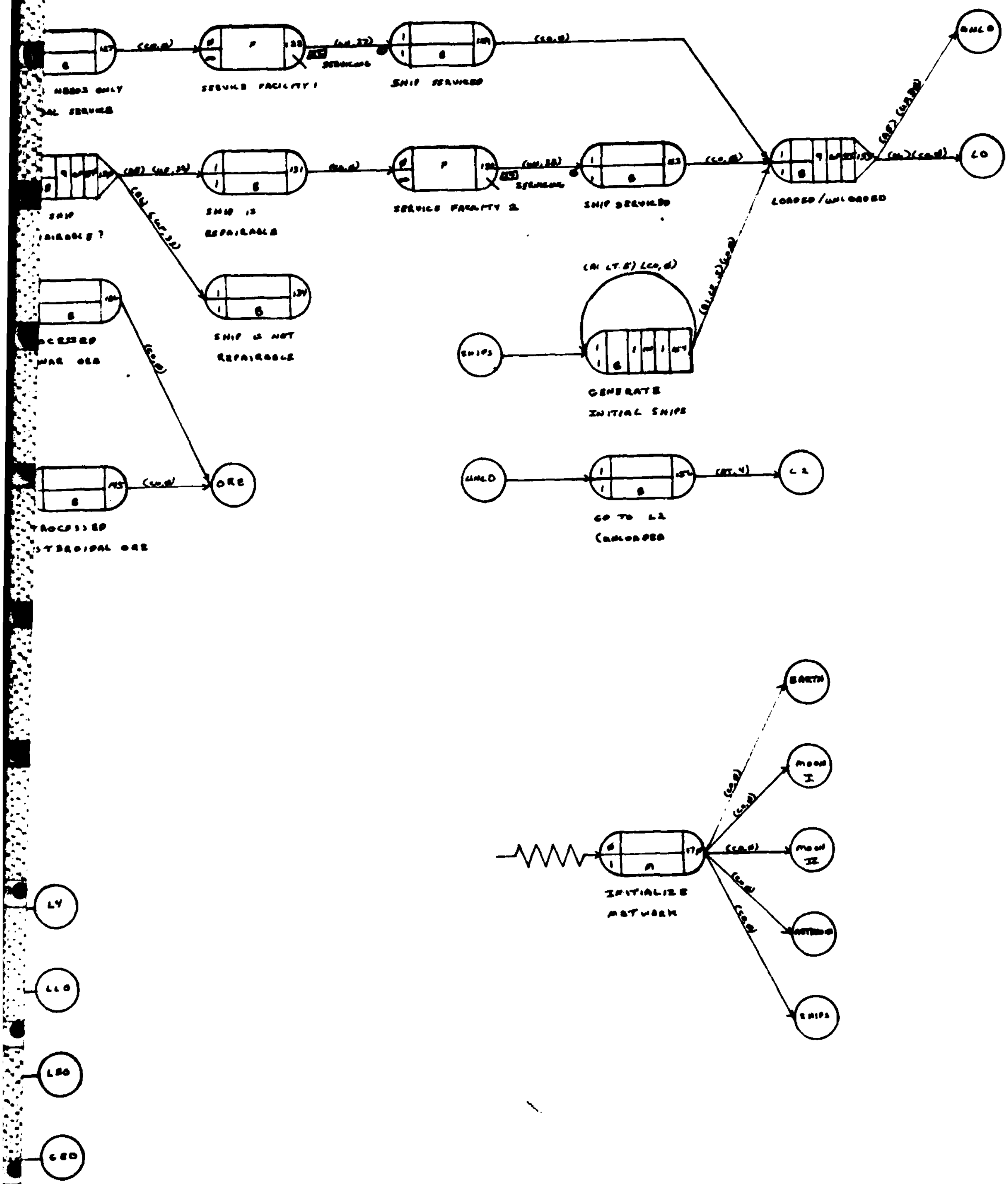
The following Q-GERT nodal description graphically depicts the transportation system for the Space Colonization and Maunufacturing System (SCMS) and the Q-GERT representation of the model.

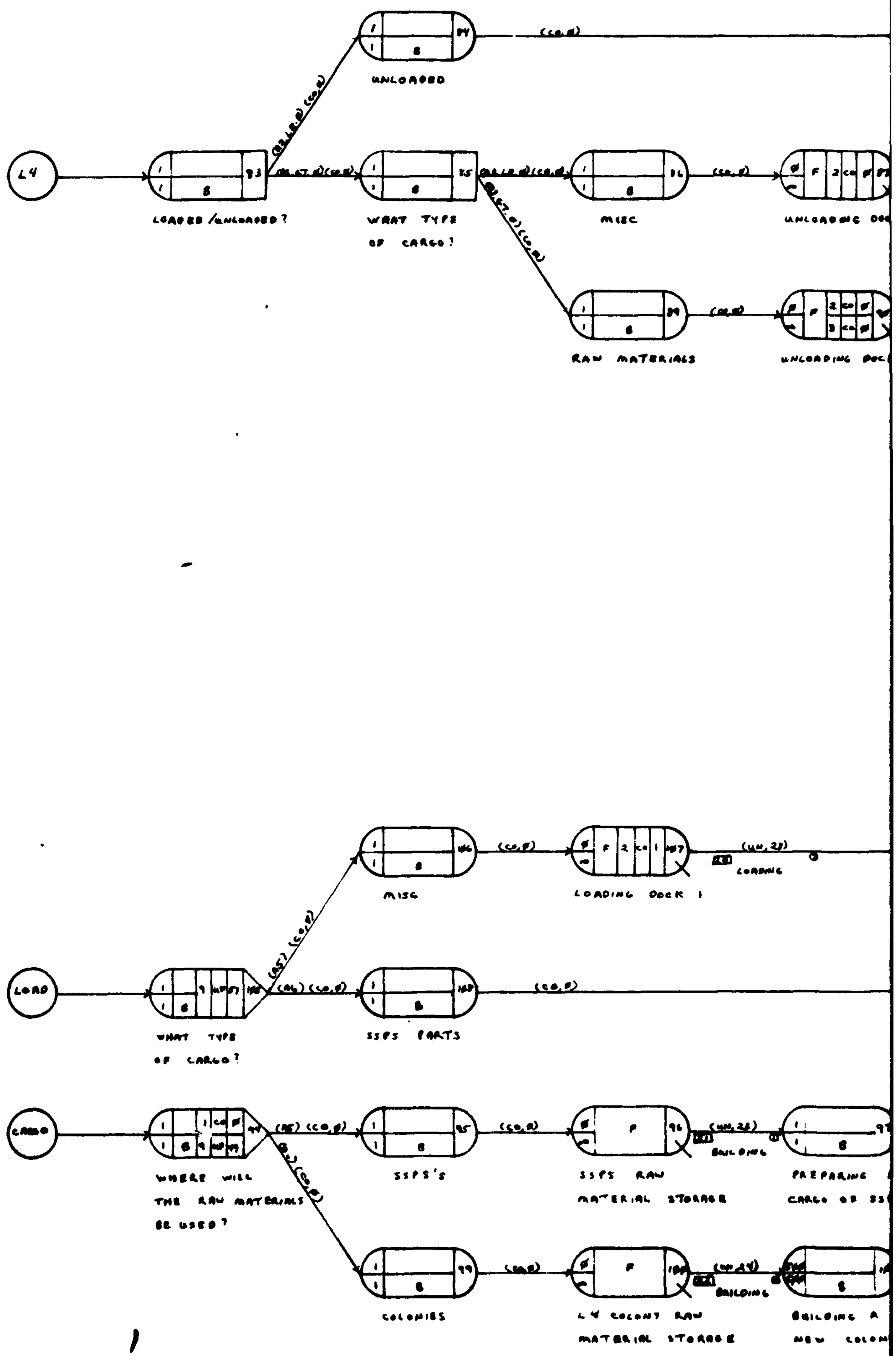

L5
WHAT TYPE OF CARGO?
MISC
UNLOADING DOCK 1
UNLOADING
SHIP UNLOADED
LUNAR ORE
UNLOADING DOCK 2
SEPARATE CARGO FROM SHIP
GET NEXT ASTEROID
ASTEROID STORAGE
ASTEROID MINER
START MINING
MINE THE ASTEROID
MINER
FREE MINER
SLAG / FUEL
ORE
WHERE/HOW WILL RAW MATERIALS BE USED?
L5 / COLONIES
L5 COLONY RAW MATERIALS STORAGE
BUILDING
BUILDING A NEW COLONY
L4
IS A SHIP AVAILABLE? L5 CARGO
GENERATE NEW SHIPS USING SUBROUTINE AS
LOADING DOCK 1
LOADING
LO
WHAT TYPE OF CARGO?
RAW MATERIALS
L5 SHIPS
MISC
LOADING DOCK 2
LOADING

/

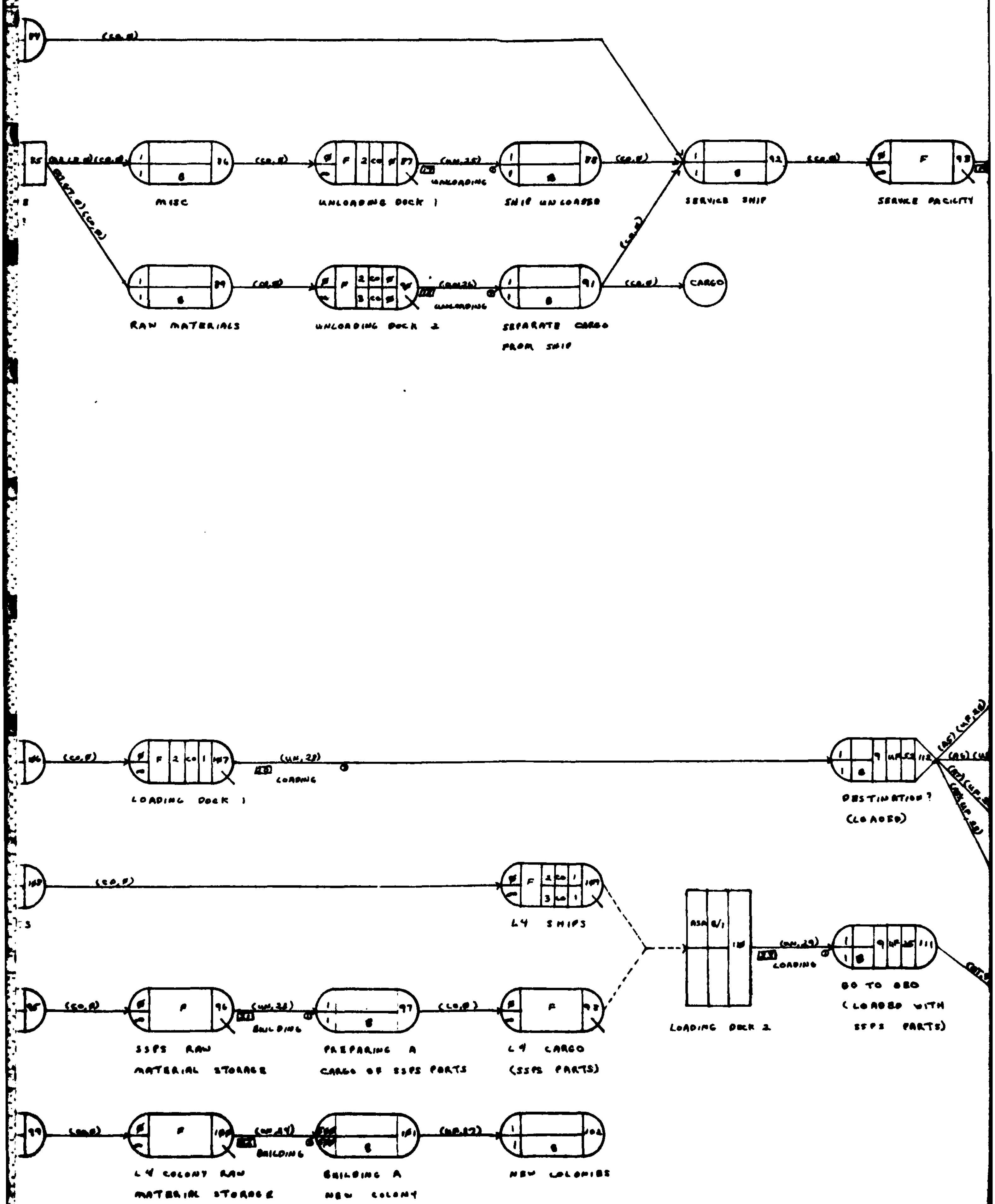


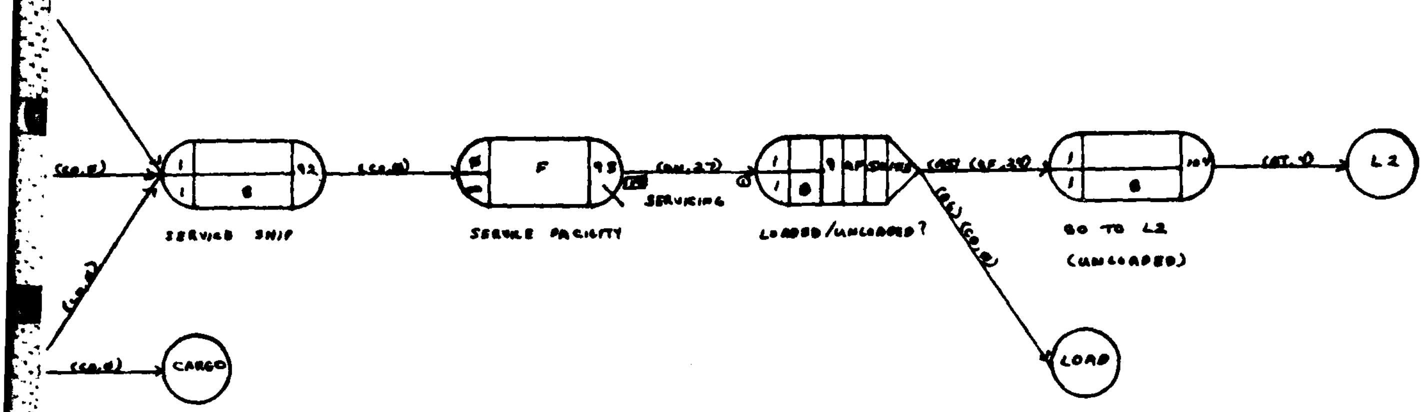
SHIP UNLOADED
IS THE SHIP'S SERVICE LIFE OVER?
SHIP'S SERVICE LIFE IS OVER
DOES SHIP NEED MAJOR REPAIRS?
SHIP NEEDS ONLY NORMAL SERVICE
IS SHIP REPAIRABLE?
SERVICE FACILITY 1
SHIP IS REPAIRABLE
SHIP IS NOT REPAIRABLE
SEPARATE CARGO FROM SHIP
PROCESSING PLANT 1 (LUNAR ORE)
PROCESSED LUNAR ORE
MINER
MINE THE ASTEROID
PROCESS THE MINED ASTEROIDAL ORE
PROCESSING PLANT 2 (ASTEROIDAL ORE)
PROCESSED ASTEROIDAL ORE
ORE
BUILDING A NEW COLONY
NEW COLONIES
L4
LOADING DOCK 1
GO TO L4 (LOADED WITH RAW MATERIALS)
L5 → L4
L5 → LLO
L5 → LEO
L5 → GEO
LLO
LEO
GEO
DESTINATION? (LOADED)

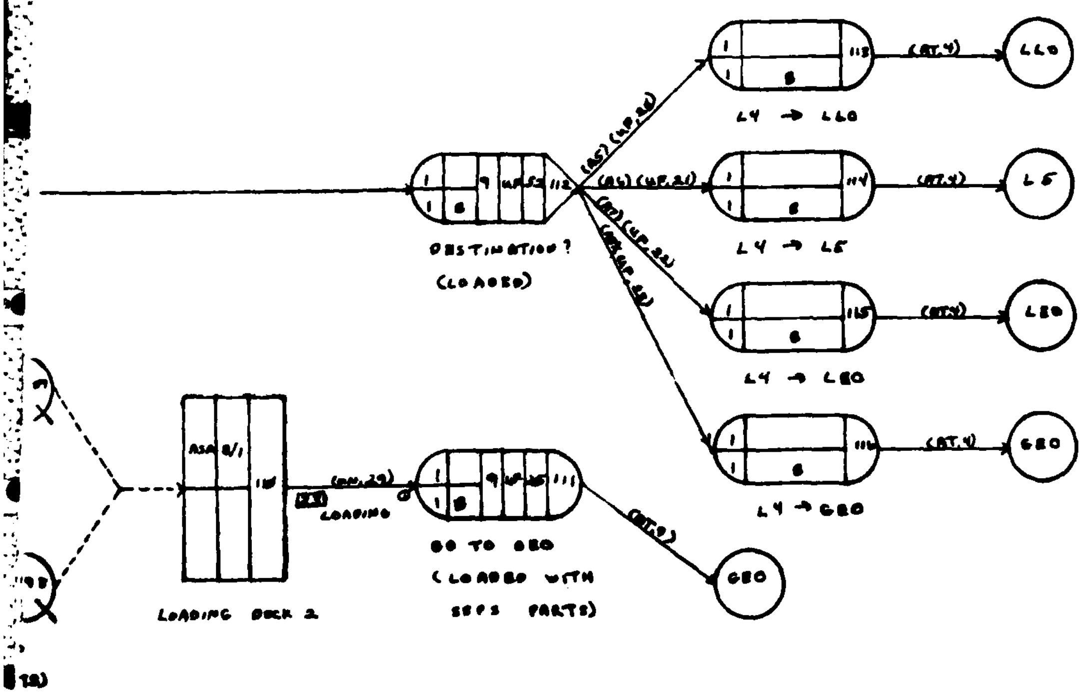

SERVICE FACILITY 1
SHIP SERVICED
SHIP IS REPAIRABLE
SERVICE FACILITY 2
SHIP SERVICED
LOADED/UNLOADED
SHIP IS NOT REPAIRABLE
GENERATE INITIAL SHIPS
SHIPS
ORE
LO
UNLD
L2
GO TO L2 (UNLOADED)
EARTH
MOON I
MOON II
SHIPS
INITIALIZE NETWORK
L4
LLO
LSO
GEO

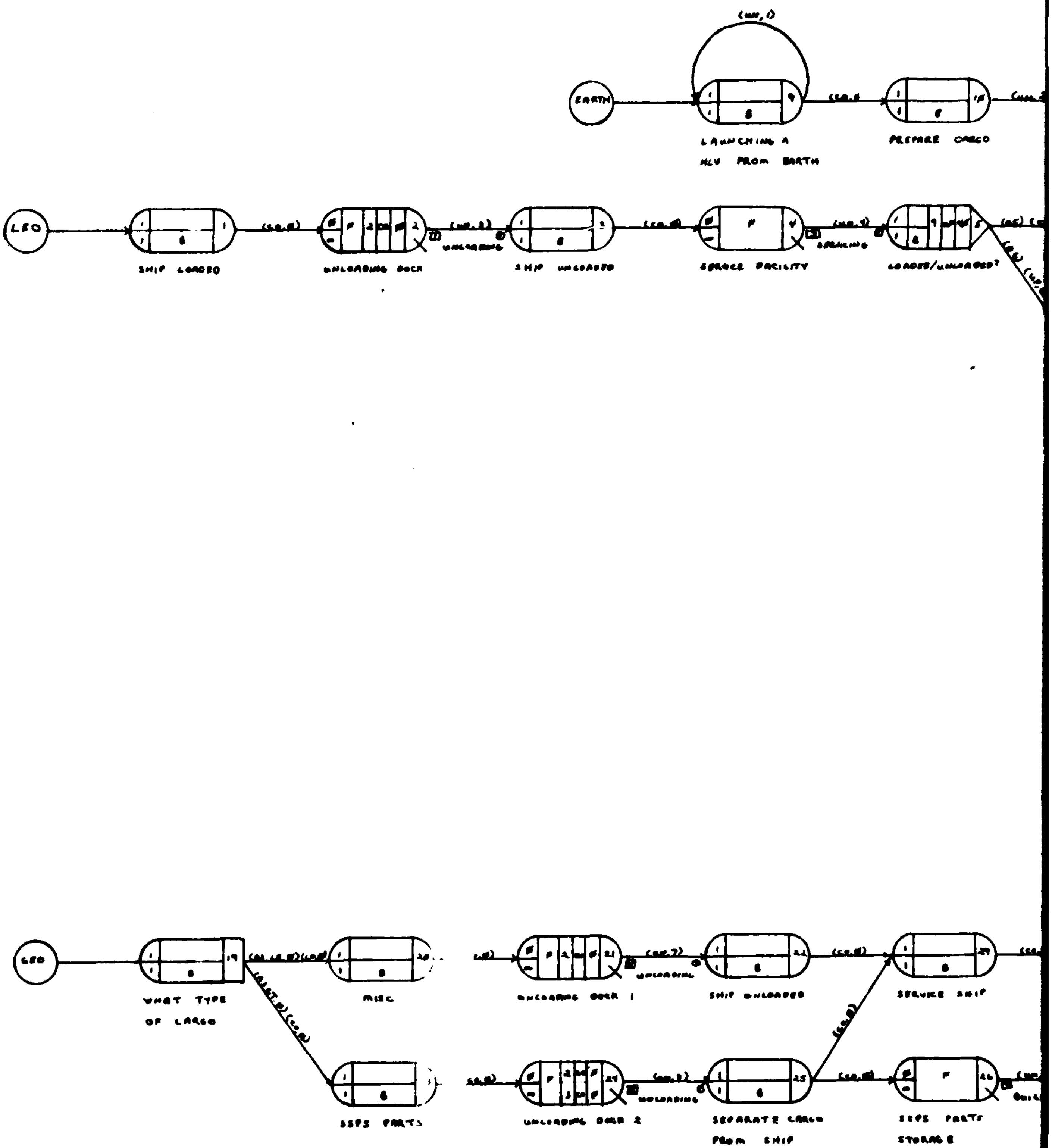


L4
UNLOADED
LOADED/UNLOADED?
WHAT TYPE OF CARGO?
MISC
UNLOADING DOC
RAW MATERIALS
UNLOADING DOC
MISC
LOADING DOCK 1
LOADING
LOAD
WHAT TYPE OF CARGO?
SSPS PARTS
CARGO
WHERE WILL THE RAW MATERIALS BE USED?
SSPS'S
SSPS RAW MATERIAL STORAGE
BUILDING
PREPARING CARGO OF SS
COLONIES
L4 COLONY RAW MATERIAL STORAGE
BUILDING
BUILDING A NEW COLON


MISC
UNLOADING
UNLOADING DOCK 1
SHIP UNLOADED
SERVICE SHIP
SERVICE FACILITY
CARGO
UNLOADING
RAW MATERIALS
UNLOADING DOCK 2
SEPARATE CARGO
FROM SHIP
LOADING
LOADING DOCK 1
DESTINATION?
(LOADED)
L4 SHIPS
LOADING
LOADING DOCK 2
GO TO GEO
(LOADED WITH
SSPS PARTS)
BUILDING
SSPS RAW
MATERIAL STORAGE
PREPARING A
CARGO OF SSPS PARTS
L4 CARGO
(SSPS PARTS)
BUILDING
L4 COLONY RAW
MATERIAL STORAGE
BUILDING A
NEW COLONY
NEW COLONIES

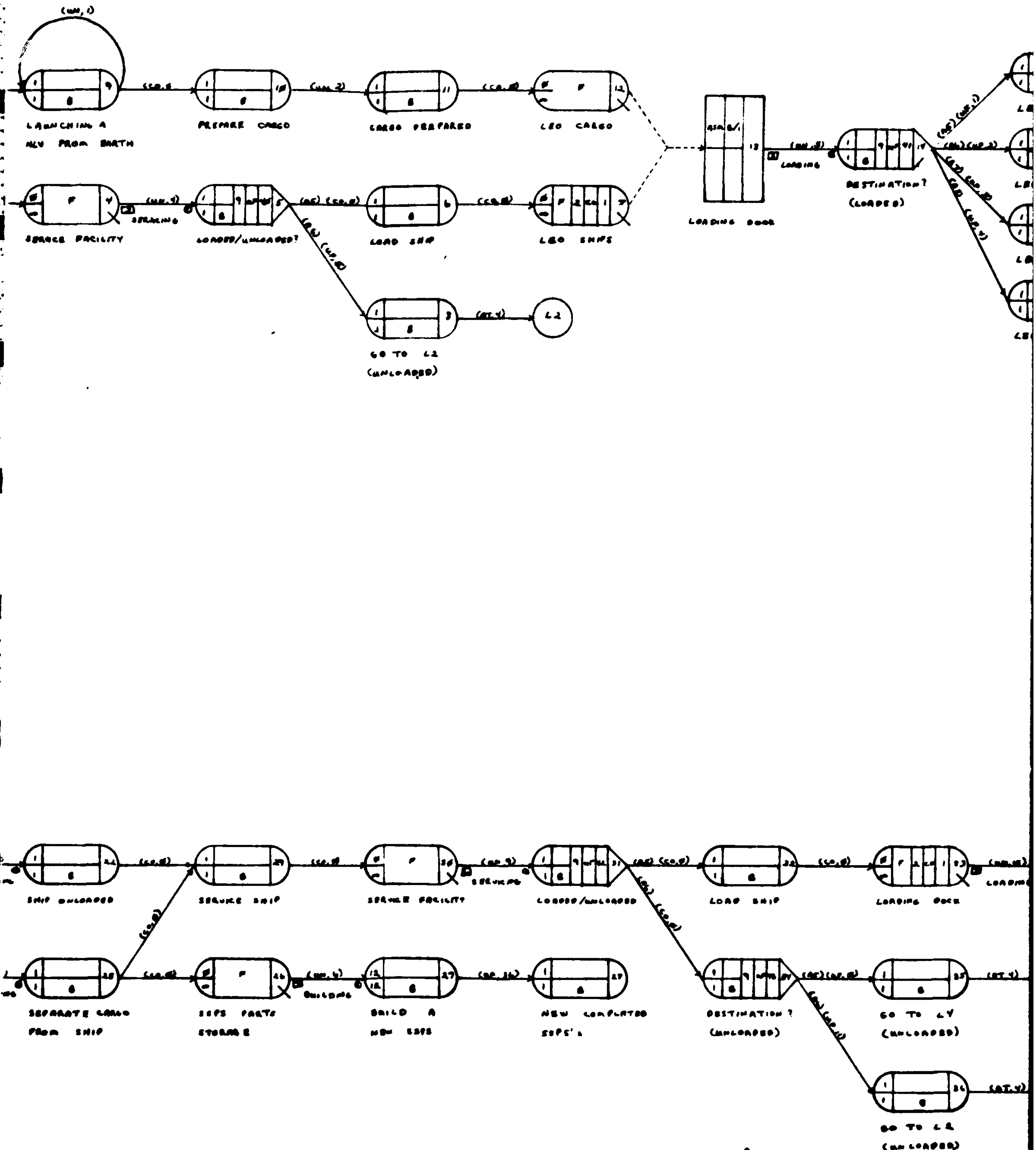

SERVICE SHIP
SERVICE FACILITY
SERVICING
LOADED/UNLOADED?
GO TO L2
(UNLOADED)
L2
CARGO
LOAD


DESTINATION?
(LOADED)
L4 → LLO
L4 → L5
L4 → LEO
L4 → GEO
LLO
L5
LEO
GEO
LOADING DOCK 2
LOADING
GO TO GEO
(LOADED WITH
SEPS PARTS)
GEO

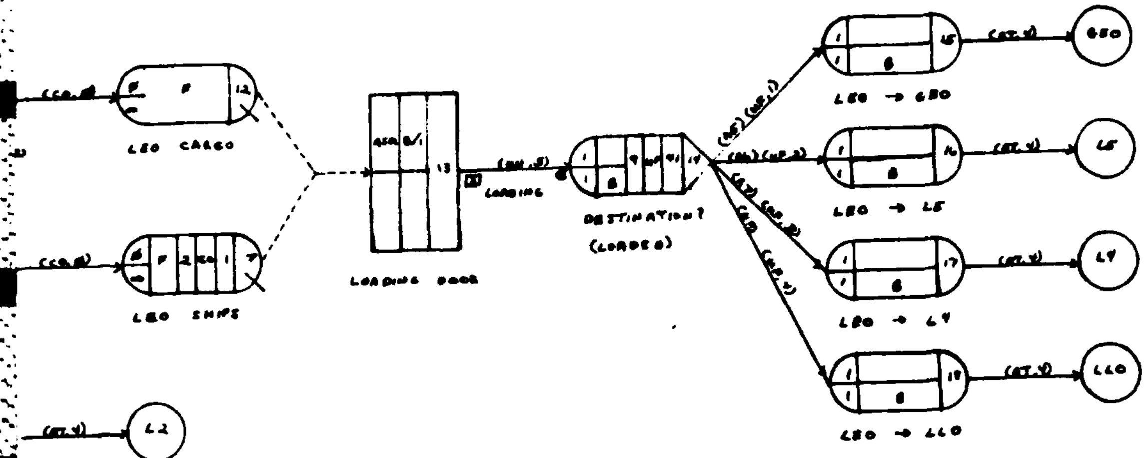


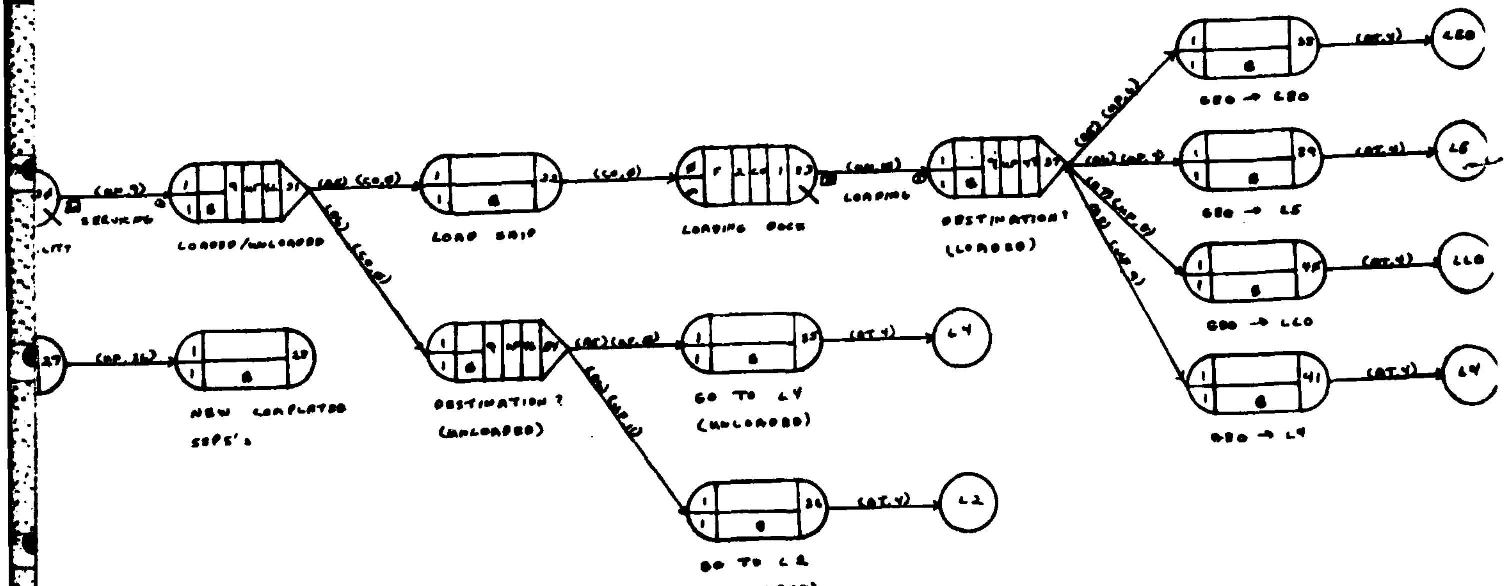
EARTH
LAUNCHING A HLV FROM EARTH
PREPARE CARGO
LEO
SHIP LOADED
UNLOADING DOCK
UNLOADING
SHIP UNLOADED
SERVICE FACILITY
SERVICING
LOADED/UNLOADED?
LEO
WHAT TYPE OF CARGO
MISC
SSPS PARTS
UNLOADING DOCK 1
UNLOADING
SHIP UNLOADED
SERVICE SHIP
UNLOADING DOCK 2
UNLOADING
SEPARATE CARGO FROM SHIP
SSPS PARTS STORAGE

1


LAUNCHING A HLV FROM EARTH
PREPARE CARGO
CARGO PREPARED
LEO CARGO
SERVICE FACILITY
SERVICING
LOADED/UNLOADED?
LOAD SHIP
LEO SHIPS
GO TO L2 (UNLOADED)
L2
LOADING DOCK
LOADING
DESTINATION? (LOADED)
SHIP UNLOADED
SERVICE SHIP
SERVICE FACILITY
LOADED/UNLOADED
LOAD SHIP
LOADING DOCK
SEPARATE CARGO FROM SHIP
SPS PARTS STORAGE
BUILDING
BUILD A NEW SPS
NEW COMPLETED SPS'S
DESTINATION? (UNLOADED)
GO TO L4 (UNLOADED)
GO TO L2 (UNLOADED)

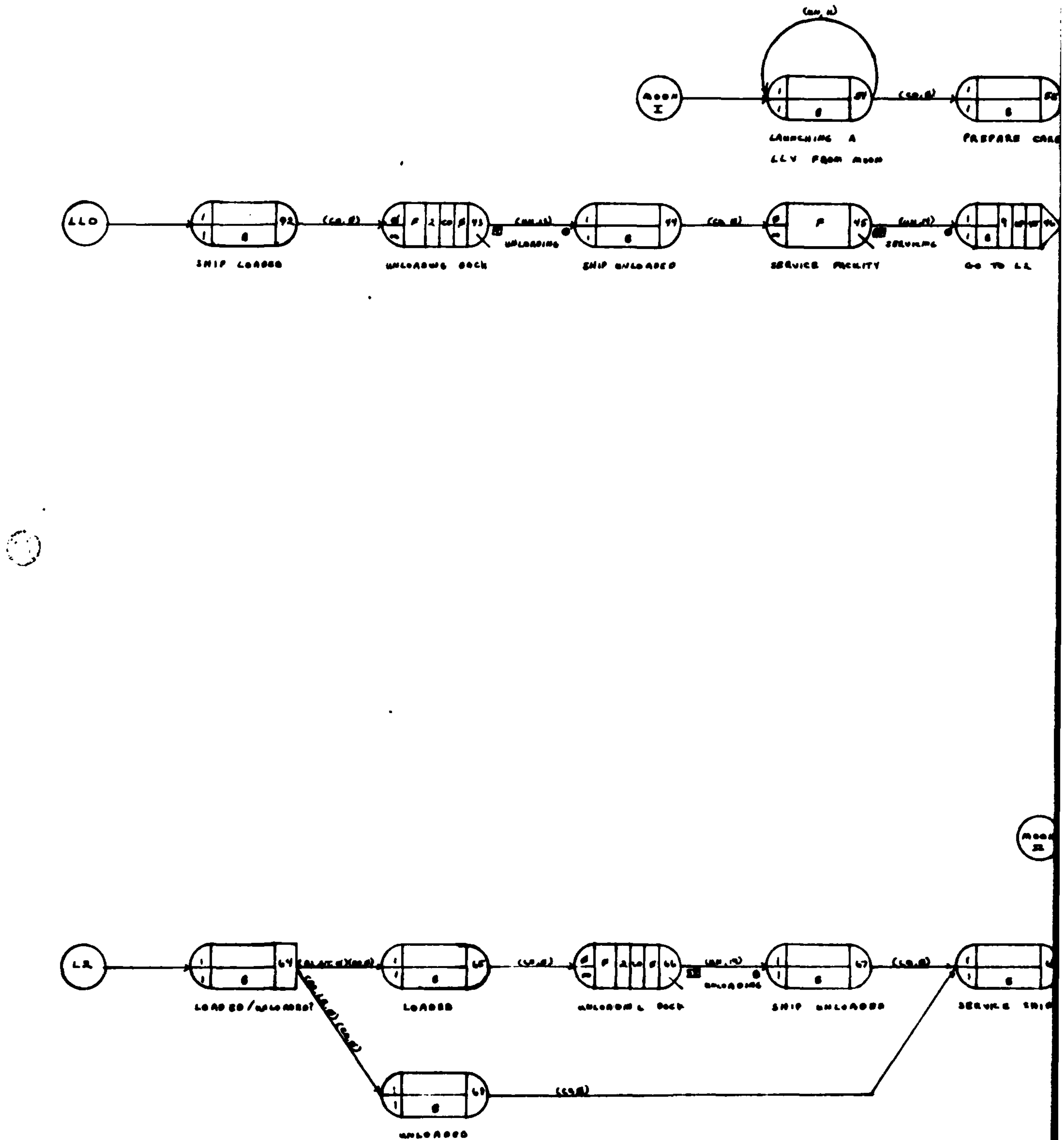
2

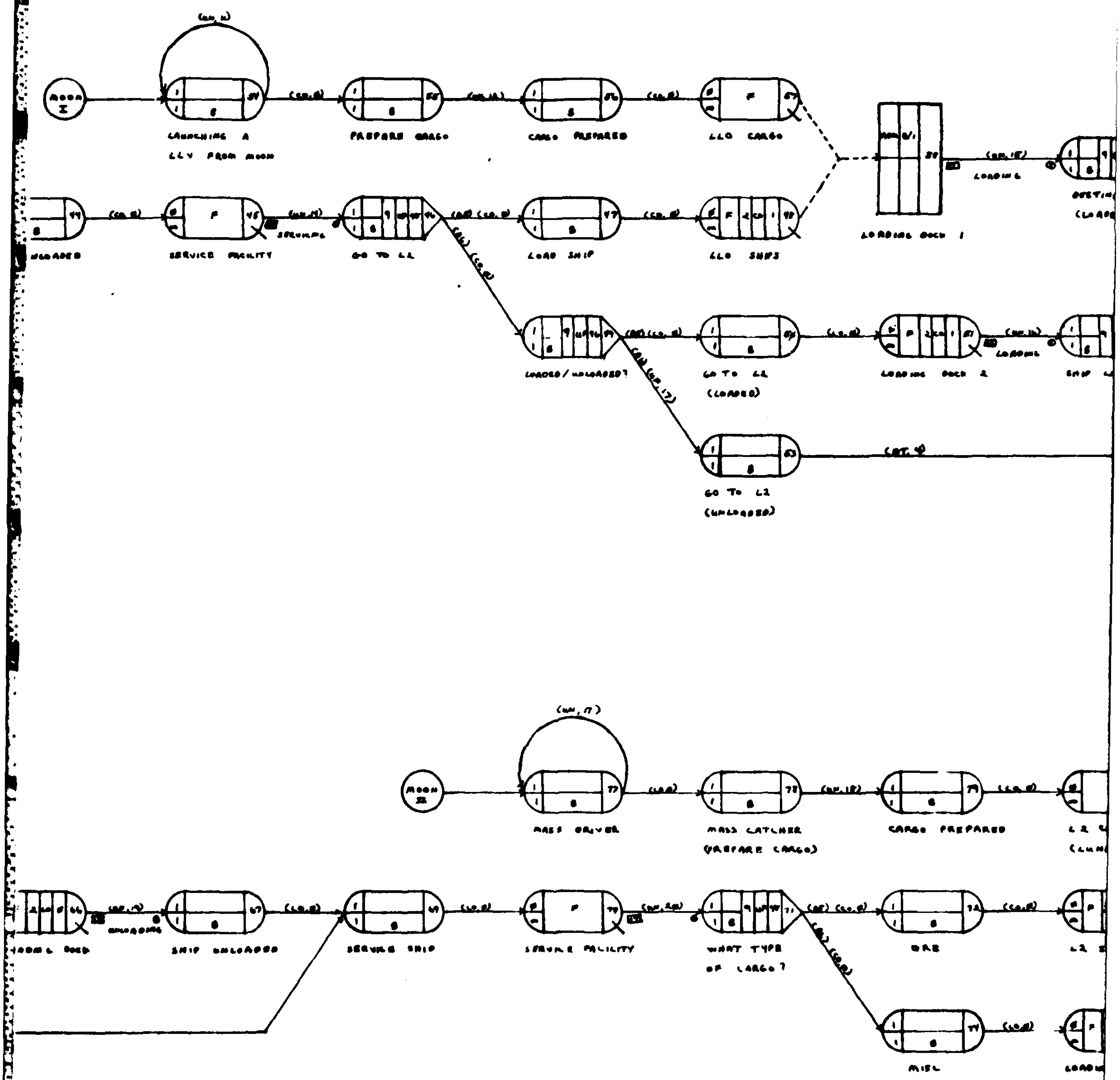

LEO CARGO
LEO SHIPS
LOADING DOCK
LOADING
DESTINATION?
(LOADED)
LEO → GEO
LEO → L5
LEO → L4
LEO → LLO
GEO
L5
L4
LLO
L2

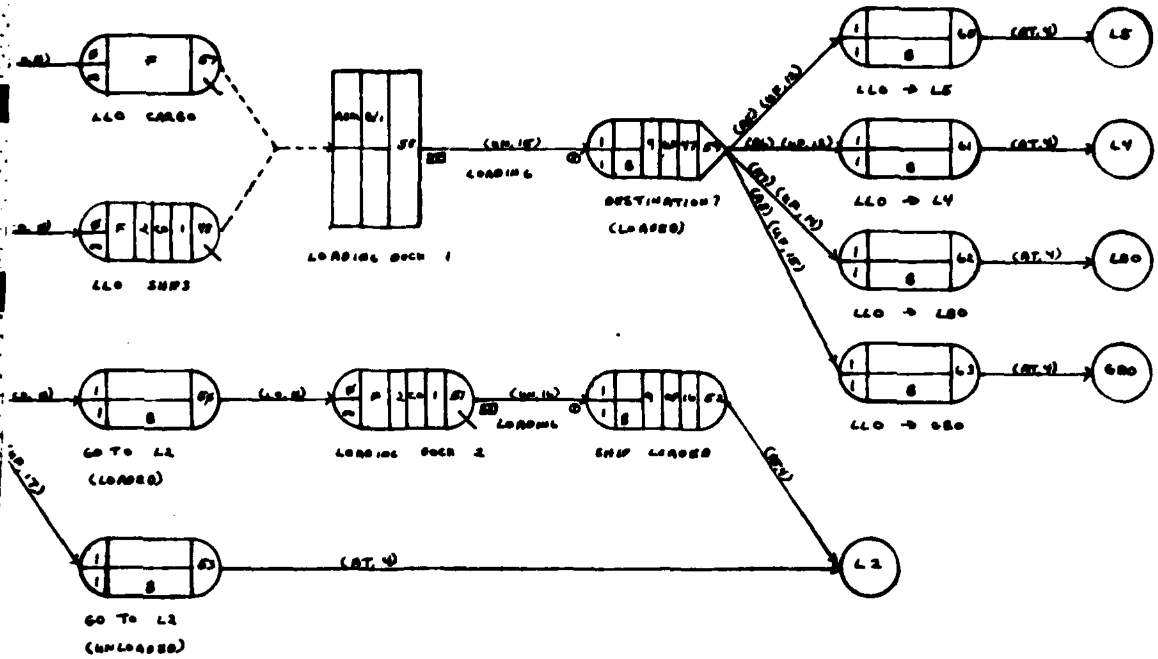

SERVICING
LOADED/UNLOADED
LOAD SHIP
LOADING DOCK
LOADING
DESTINATION?
(LOADED)
GEO → LEO
GEO → L5
GEO → LLO
GEO → L4
LEO
L5
LLO
L4
NEW COMPLETED
SPS's
DESTINATION?
(UNLOADED)
GO TO L4
(UNLOADED)
GO TO L2
(UNLOADED)
L4
L2

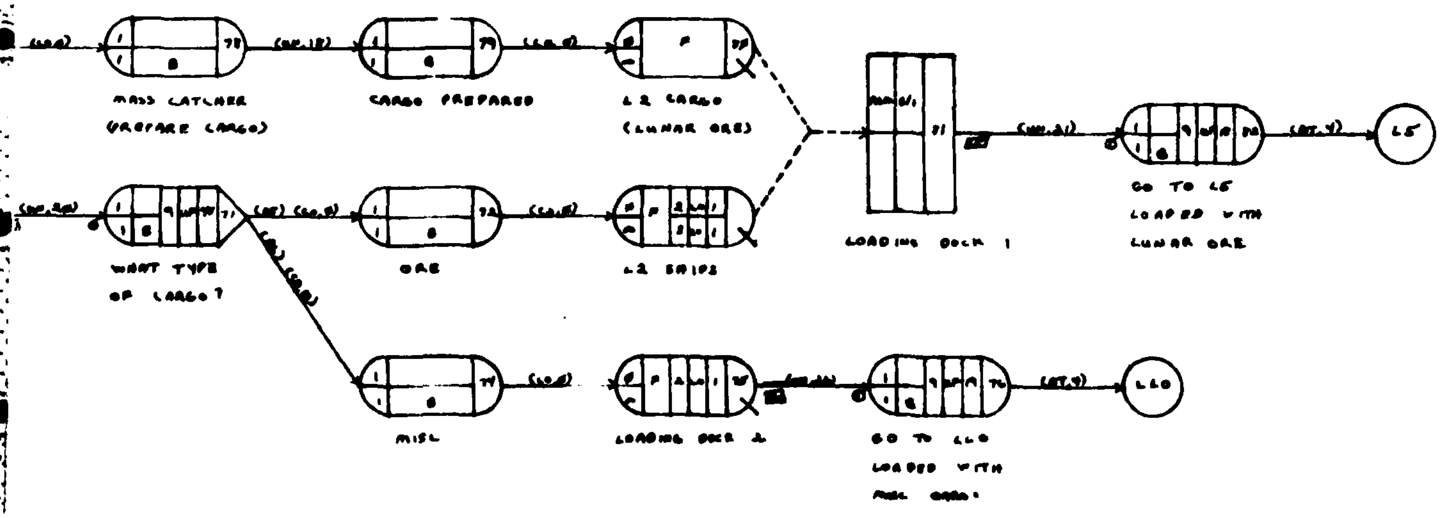
2

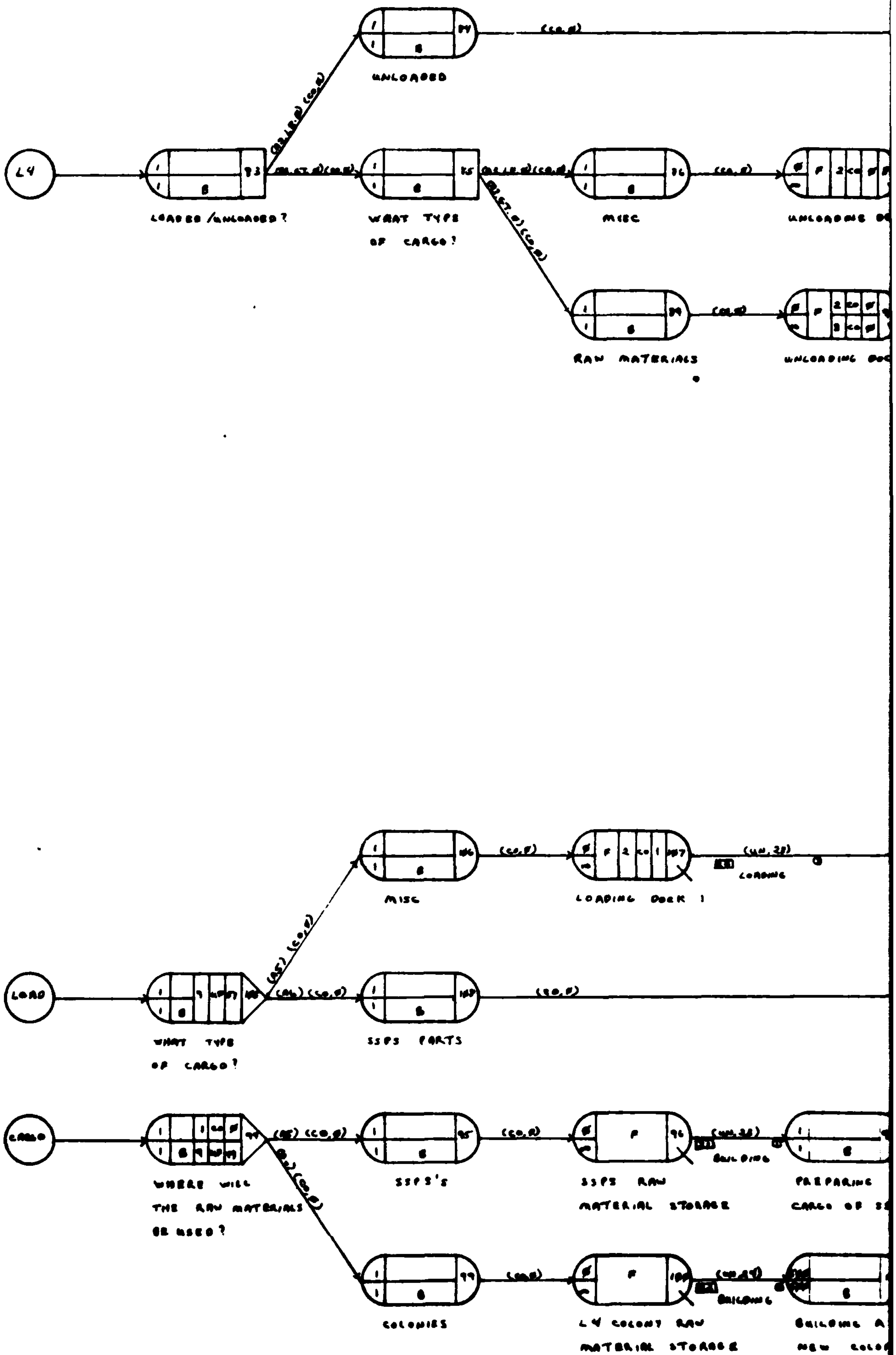
3


MOON I
LAUNCHING A LLV FROM MOON
LLO
SHIP LOADED
UNLOADING DOCK
UNLOADING
SHIP UNLOADED
SERVICE FACILITY
SERVING
GO TO LL
LL
LOADED
UNLOADING DOCK
UNLOADING
SHIP UNLOADED
UNLOADED

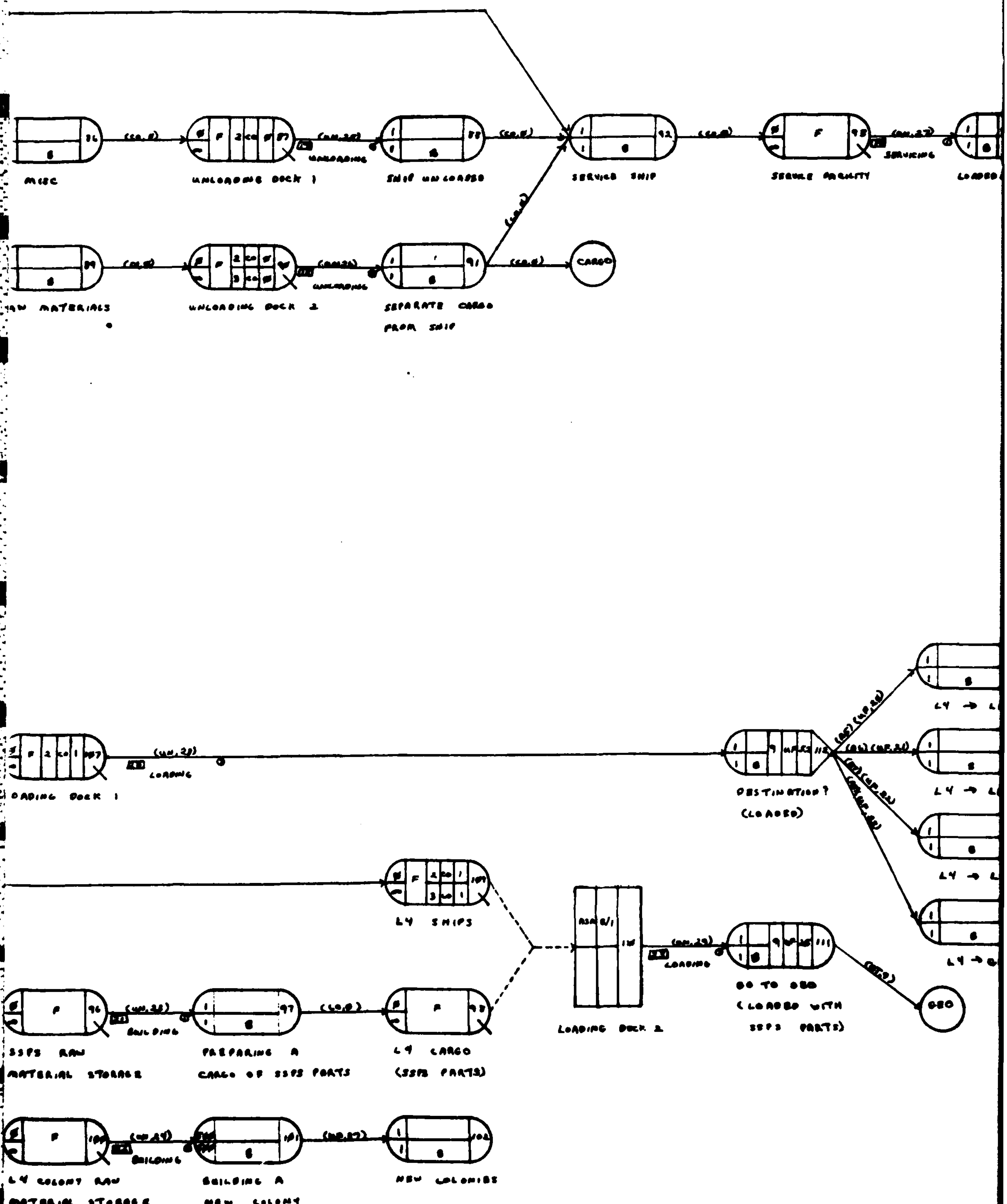

MOON I
LAUNCHING A LLV FROM MOON
PREPARE CARGO
CARGO PREPARED
LLO CARGO
LOADING DOCK 1
LOADING
SERVICE FACILITY
SERVICING
GO TO L1
LOAD SHIP
LLO SHIPS
LOADED/UNLOADED?
GO TO L2 (LOADED)
LOADING DOCK 2
GO TO L2 (UNLOADED)
MOON II
MASS DRIVER
MASS CATCHER (PREPARE CARGO)
CARGO PREPARED
UNLOADING
SHIP UNLOADED
SERVICE SHIP
SERVICE FACILITY
WHAT TYPE OF CARGO?
ORE
MISC


LLO CARGO
LLO SHIPS
LOADING DOCK 1
LOADING
DESTINATION?
(LOADED)
LLO → L5
LLO → L4
L5
L4
(AT,4)
GO TO L2
(LOADED)
LOADING DOCK 2
LOADING
SHIP LOADED
GO TO L2
(UNLOADED)
L2

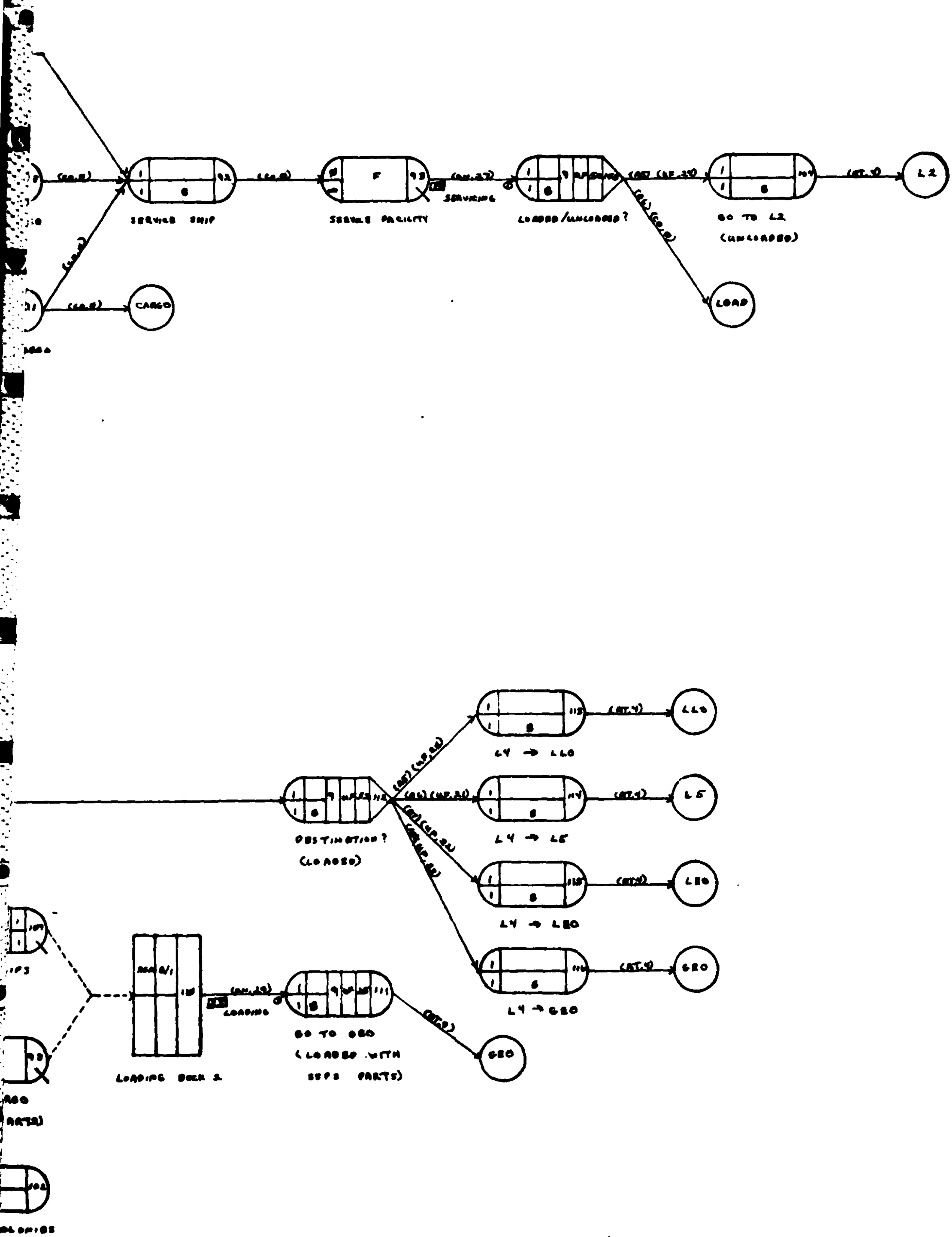

MASS CATCHER
(PREPARE CARGO)
CARGO PREPARED
L2 CARGO
(LUNAR ORE)
LOADING DOCK 1
GO TO L5
LOADED WITH
LUNAR ORE
L5
WHAT TYPE
OF CARGO?
ORE
L2 SHIPS
MISC
LOADING DOCK 2
GO TO LLO
LOADED WITH
LLO
(AT,4)



L4
LOADED /UNLOADED?
UNLOADED
WHAT TYPE
OF CARGO?
MISC
RAW MATERIALS
LOAD
WHAT TYPE
OF CARGO?
MISC
LOADING DOCK 1
SSPS PARTS
CARGO
WHERE WILL
THE RAW MATERIALS
BE USED?
SSPS'S
SSPS RAW
MATERIAL STORAGE
COLONIES
L4 COLONY RAW
MATERIAL STORAGE



MISC
UNLOADING DOCK 1
SHIP UNLOADED
SERVICE SHIP
SERVICE FACILITY
UNLOADING
SERVICING
RAW MATERIALS
UNLOADING DOCK 2
SEPARATE CARGO FROM SHIP
CARGO
LOADING DOCK 1
LOADING
DESTINATION? (LOADED)
L4 SHIPS
LOADING DOCK 2
GO TO GEO (LOADED WITH SSPS PARTS)
GEO
SSPS RAW MATERIAL STORAGE
BUILDING
PREPARING A CARGO OF SSPS PARTS
L4 CARGO (SSPS PARTS)
L4 COLONY RAW MATERIAL STORAGE
BUILDING A NEW COLONY
NEW COLONIES



SERVICE SHIP
SERVICE FACILITY
SERVICING
LOADED/UNLOADED?
GO TO L2
(UNLOADED)
L2
LOAD
CARGO
DESTINATION?
(LOADED)
L4 → LLO
L4 → L5
L4 → LEO
L4 → GEO
LLO
L5
LEO
GEO
LOADING DOCK 2
LOADING
GO TO GEO
(LOADED WITH
SSPS PARTS)
GEO

VITA

Lynn Arthur Wagner, Jr. was born on August 21, 1950 in Dubuque, Iowa, to Lynn A. and Adeline Adele (Schmidt) Wagner. He graduated from Verona Union High School in Verona, Wisconsin, and attended the University of Wisconsin, Madison, Wisconsin. He enlisted in the U. S. Marine Corps in 1969, served in Veitnam and Southeast Asia, and achieved the rank of Lance Corporal (E-3) before being honorably discharged in 1971. After leaving the Marine Corps, he again attended the University of Wisconsin from which he recieved the degree of Bachelor of Science in Chemistry and Mathematics in June 1975. He entered the U. S. Air Force on active duty in October 1976 and recieved his commission from Officer Training School in February 1977. He completed Space Systems Analyst and Space Object Identification Analyst courses in 1977 while serving as a Space Systems Analyst with the Intelligence Directorate in the Headquarters of the Aerospace Defence Command (ADCOM) at Peterson AFB, Colorado. In 1980 while at ADCOM, he was sent to the University of Wisconsin under Operations Bootstrap to complete a major in Computer Science. After leaving ADCOM, he served as a Balistic Missile Performance Analyst with the Foriegn Technology Division at Wright Patterson AFB, Ohio, until entering the School of Engineering, Air Force Institute of Technology, in June 1981. He is a member of the AIAA, Tau Beta Pi, and Alpha Iota Delta.

Permanent address: 3534 Concord Avenue
Madison, Wisconsin 53704

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computer simulation model of a transportation system for a hypothetical Space Colonization and Manufacturing System (SCMS) was developed to show how the transportation system will possibly function. The model, written in Q-GERT, a simulation language which allows a graphical presentation of the system, could be modified to experiment with different transportation strategies. While the SCMS is based mostly on current information, it is very likely that an entirely different system will eventually be developed. With this being the

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) case, the main objective was not to just build a model for a particular system but to illustrate a methodology which could be used with another system.

The SCMS consists of six facilities in different orbits: three situated at Lagrangian points of the Earth-Moon system and the other three in low Earth orbit, geostationary Earth orbit, and low lunar orbit. The main activities of the SCMS are to build space colonies, to build Satellite Solar Power Stations, and to process lunar and asteroidal ore. The major component of the transportation system is the Inter-Orbital Shuttle which moves most goods between the points in the SCMS and is unloaded, serviced, and loaded at each of the facilities.

END

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